IMPACT OF CLIMATE VARIABILITY AND CHANGE ON SORGHUM PRODUCTION IN THE LOWER SHIRE VALLEY IN MALAWI

By

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Declaration of originality

I hereby declare that this work is entirely my own and not of any other person, and it has not previously been submitted in any form to the University of Nairobi or to any other institution for assessment for any other purpose.

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ABSTRACT

Climate change is likely going to cause changes in the weather patterns over Malawi, which may include the extreme episodes of rainfall and temperatures. Such drastic weather changes will have serious impacts on food security in various parts of the country. To cope with such extreme changes, factors influencing them need to be understood. A simulation study was carried out using APSIM Model to assess the potential sensitivity of sorghum yield to likely changes in temperatures and rainfall in the Shire Valley. Three fertilizer management practices which include "No application" (0) kg/ha fertilizer, 25kg/ha of Urea, 50kg.ha Urea were used in the assessment their contribution towards yield loss.

Impacts of changes in temperature, rainfall and CO_2 concentration was determined using individual candidate first and then combined effects of these variables. Analysis for the projection of period 2046-65 was done with CO_2 concentration of 570ppm, T_{min}+1.8°C, T_{max}+1.6°C, and for 2070-2100 CO_2 concentration of 700ppm, T_{min} and T_{max} of 3.0°C, rainfall of −16% conditions. Rainfall intensity was changed to modify the historical rainfall data by rainfall of −9% for 2046-2065 and -16% for 2070-2100. Comparison of that present (observed) and future (CSIRO model) climate variability showed increase in temperatures by 9% by 2060 while rainfall declined by 14.7%. Extreme events such as number of dry days and high night time temperature have also increased with a dramatic decrease of number of cold days.

The study demonstrated that by 2030, Shire Valley's seasonal temperature will increase by 3°C causing an average reduction in the yield by 13% (0kg/ha), 8.8% (25kg/ha) and 7.6% (50kg/ha). Changes in seasonal total rainfall of 16% showed a decreased in yield by 43kg/ha per year. Such impacts would make Malawi a food insecure nation by 2060. Hybrid variety was more sensitive to effect of temperature changes in 2070-2100, while local variety (Thengalamanga) was more sensitive to rainfall reduction during the same period. Locally variety could be more beneficial to increase in temperatures while CO_2 concentration would reduce yield in both variety. Fertilizer application of 25kg/ha of land and 50kg/ha showed that yield would increase by 14% and 63% respectively even in an event of 1.6°C temperatures rise.

This study highlights that, in addition to changes in intra-seasonal variability of rainfall, increased trend in consecutive number of dry days (CDD) will also be important for future yields in the Shire Valley. In addition to this, the study suggest for a need to invest in improving the temperature and radiation records in the study area to enhance understanding of their relationships to crop production.

***Keywords** Extreme events; crop simulation model; crop yields, APSIM, CSIRO MK3.6, Cultivar.*

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Dedicated to-

HOFO, who in many ways are striving to treadle the path I walked

Table of Contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

AGCM=Atmospheric General Circulation Model
APSIM= Agricultural Production Systems sIMulator
CMIP5= Coupled Model Inter-comparison Project Phase 5
CCI/CLIVAR = **Change Detection and Indices/Climate Variability and Predictability**
CSIRO = The Commonwealth Scientific and Industrial Research Organisation
DCCMS = Department of Climate Change and Meteorological Services
ENSO= El Niño-Southern Oscillation
GCM = General Circulation Model (Global Climate Model)
GHG = Green House Gases
GDFRR= Global Facility for Disaster Reduction and Recovery
ICRISAT =International Crop Research Institute for Semi-Arid Tropics
IPCC = Intergovernmental Panel on Climate Change
IFAD = International Fund for Agriculture Development
ETCCDMI = Expert Team for Climate Change Detection Monitoring and Indices.
FANRPAN = Food, Agriculture and Natural Resources Policy Analysis Network
FAO = Food Agriculture Organisation
ICRA = International Centre for development oriented Research in Agriculture
KNMI = Koninklijk Nederlands Meteorologisch Instituut
MVAC =Malawi Vulnerability Assessment Committee
NAPA = National Adaptation Programmes of Action
OGCM =Ocean General Circulation Model
SVADD = Shire Valley Agriculture Development Division
SRES = Special Report on Emission Scenarios
TAR = Third Assessment Report
TGICA = The Task Group on Scenarios for Climate and Impact Assessment
UNFCCC = United Nations Framework Convention on Climate Change
UNDP = United Nation Development Programme
HI =Harvesting Index
WUE = Water Use Efficiency

CHAPTER ONE

1.0 INTRODUCTION

1.1 Study Background

Malawi is one of the least developed and most densely populated countries in the world. While globally agriculture contributes 24% of the world output and uses 40% of world total land area (*FAO, 2007*), in Malawi it accounts for 39% of GDP and 90% of export revenues (*World Bank, 2010*). Agriculture is the source of income for more than 80% of population apart from substantial inflows of foreign aid from the IMF, the World Bank, and individual donor nations (IMF, 2008) and employs over 80% of the country's labour force (*MVAC, 2010; NAPA, 2006*). The population of Malawi was pegged at 15,263,000 in 2009 with an increase rate of 2.8%/ann. (*NSO 2008 Census*). Approximately 90% of the population is classified as poor and those particularly in the rural areas rely mainly on rain-fed agriculture for their livelihoods. With a narrow economic base, limited agro-based processing industries, over dependency on a single season rain fed agriculture; the country is highly vulnerable to the adverse impacts of extreme weather events associated with climate variability and climate change (Butterworth *et.al*, 2010). Increasing population pressure, limited land resource base, land degradation arising from agricultural expansion exacerbates poverty among the population (*NSO, 2008*). According to a report published in 2010 by World Bank, 1.846188 hectares of land was under cereal production in 2009, as compared to 1780120 hectares in 2008. Land under cereal production here refers to harvested area, although some countries report only sown or cultivated area. These cereals include wheat, rice, maize, barley, oats, rye, millet, sorghum, buckwheat, and mixed grains.
Sorghum is one of the major food crops grown in the semi-arid climatic conditions of Malawi due to its capability to withstand drought conditions. The crop is particularly common and variable in the lowlands along the eastern shore of Lake Malawi (the areas of Salima, Mangochi and between Chiradzulu and Phalombe) and in the Shire Valley (*IPGR, 2010*). Sorghum gained popularity in the drought prone areas of the country due to increase in the frequency of extreme climatic conditions. Drought and floods have resulted into depressing to complete removing maize growth as staple food. The total area of sorghum production varied from 14,000 to 22,000 ha between 1977 and 1987, with average yields of 370-800 kg/ha (compare 2000 kg/ha on station). Though sorghum is widely grown in the country (from 100 to 2000 masl), the main area of cultivation is the Lower Shire Valley, where the crop accounts for up to 60% of the cultivated

area. This region accounts for 75% of Malawi's sorghum grain production (though 5-10% of its population). A secondary concentration of sorghum cultivation is the hilly region of the extreme north of the country, near Karonga. In contrast to the relatively dry Shire Valley, here average annual rainfall is 1000-2000 mm, *(Chintu et al.1996; Appa Rao et al. 1989).*

Although sorghum is a drought resistant crop, it is also adversely affected by climate variability and change, management practices and socio economic factors like any other crop. In the last three decades, unpredictability of seasonal rainfall and climate variability resulted in a huge impact on the agricultural sector. Crop failures due to prolonged dry spell and droughts have increased. Since 1970, six major droughts (1978/79, 1981/82, 1991/1992, 1994/95 2001/2002 and 2004/2005) disrupted the country both socially and economically (*MVAC, 2005; ActionAid, 2008*). During these years, total annual rainfall was between 400 to 800mm which was hardly enough to sustain maize production which is the country's staple food. These droughts adversely affected the agriculture, water, forestry, fisheries and wildlife sectors among others (*Mkanda, et. al., 1995; NAPA, 2006*). Variability in climate associated with increased weather extremes resulted in shifts of rainfall onset dates, reducing crop growing period, frequent floods, prolonged dry spells and chronic droughts, (*NAPA 2006).* According to *IPCC (2007),* the impacts of climate variability and change are on the increase and unavoidable. The poor communities are highly susceptible to these impacts due to low capacity to adapt to the adverse impacts of climate change, a condition that aggravates the food security risks (*UNFCC, 2007; MVAC, 2010*).

1.2 Statement of the Problem

The population of Malawi is projected to increase to approximately 40 million by 2050. This increase would seriously affect food security and livelihoods for most of the vulnerable people (*PRB, 2011*). Although different General Circulation Models have projected different climatic scenarios for Malawi, between 1960-2006 temperature has risen by 0.9°C (*McSweeney, et al., 2008*) and is projected to continue increasing by 1- 2.5°C, while rainfall is expected to decrease by 16% by 2030 (*Tearfund, 2010*). With these rapid increases in temperatures and decline in rainfall, crop production would become a challenge. The southern part of the country where Shire Valley lies, is one of the areas already impacted by changes in the climate elements which ranges from severe droughts as in 1991/92 to extreme flooding events in 2000/01 (*MVAC, 2010*). With continual variation in the climate variables (weather elements), agriculture productions in the area, particularly cereals, will be adversely affected.

Some research institutes such as International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and Agriculture Research Extension Trust (ARET) operating in Malawi have noted that impact of climate change on agricultural production is adverse citing frequency of drought, floods and prolonged dry spells. For example, there has been serious fluctuation of average rainfall between 1979-2001, dominated by dry spells, floods and droughts. The most serious droughts occurred in 1979 (lasting 30 days) followed by 1991 with 26 days and 1990 with 21 days (*IPGRI, 2002*). The challenge now is to establish future trends of these fluctuations and their impact on crop yields of major cereal crops. To establish how these crops would withstand future climate variability and change.

There is scanty information about the plausible impact of climate change under the projected future scenarios of categories A1B and A2 on sorghum yields in Malawi particularly the Shire Valley. This study therefore seeks to determine the effect of climate variation on sorghum production in the Shire valley of Malawi with a view to recommending adaptation strategies that could enhance sorghum productivity in Malawi.

1.3 Research Question

What impact will climate change have on future sorghum yield in the lower Shire Valley of Malawi?

1.4 Objectives of the Study

The main objective of this study is to investigate the impact of climate variability and change on rain fed sorghum production in the Shire Valley of Malawi.

The specific objectives of the study will include

1) Determination of the trend and variability in the rainfall and temperatures in the Shire Valley.
2) Determination of the effect of climate on sorghum production in the Shire Valley.
3) Determining the future climate for Shire Valley based on A2 and A1B of the GCM climate change scenarios.
4) Model the potential impacts of climate change on sorghum production in the short, medium and long term.

1.5 Justification of the Study

Agriculture remains the only major source of income in terms of employment and foreign exchange earning in Malawi (*FAO, 2007; Deloitte, 2011*). Agriculture systems in the country are mainly rain-fed making them more sensitive to climate variability and change. The Lower Shire Valley, which lies on the extreme end of southern Malawi, is under a semi-arid savannah climatic regime, making the area quite vulnerable to the adverse impacts of climate variability and change.

The Shire Valley experiences quite frequent dry spells, flooding and drought; and comprises of large closed area of degraded land that gives rise to increase crop failure leading to food insecurity. This has posed a challenge to the community by significantly threatening food security of the areas. In addition, Malawi have been projected to be severely affected by the adverse effects of climate change such as dry spells, droughts, floods altered rainfall seasons (*IPCC, 2007*). Climate variability has in the recent past been manifested in these extreme climate events and has significantly been destructive and disruptive to the farming activities in the area (*ActionAid, 2008*) thereby severely affecting food security in the area (*World Bank, 2010; NSO 2008*). There is need to understand these variability with an intention of reducing their impacts on crop production particularly sorghum in the areas. Frequent exposure of agricultural systems to extreme climatic events such as floods, drought and prolonged dry spells in the area has perpetuated food insecurity and poverty (*GFDDR, 2011; MVAC, 2010; Nangoma, 2007*).

Most studies related to the interaction between crops and climate in the area have concentrated more on crops such as maize, rice, cotton cultivar improvement, pests and diseases. Very little research work has been done on sorghum in relation to its interaction with climate (*Taylor, 2002*). Sorghum being one of the most drought tolerant crops has maintained its popularity among farmers in the regions where weather is very unpredictable (*Singh, et al., 1997; USAID, 2009*). From vulnerability assessments that have been conducted in the region, drought and prolonged dry spells have been noted as responsible even for the genetic erosion of the sorghum crop varieties, *(IPGRI, 2002)*. An understanding of future climate change impacts on sorghum would therefore help not only in getting high yields, but also in guarding the existing sorghum varieties from genetic erosion, (*Chintu, 1996; FAST, 2008*).

The major national priority by the Government of Malawi as enshrined in its Growth and Development Strategy (MGDS) for the period 2006–2011 is to achieve and sustain the Millennium Development Goals (MDGs) with the aim of making Malawi a hunger free nation

(*MDGS 2006-11, NAPA, 2006*). Since Society is impacted more by changes in extremes than by changes in means, this study therefore targets to contribute towards this very important national priority focal area.

1.6 Study Area

1.6.1 Area of Study

The area of study was Shire valley which is composed of two districts, Chikwawa and Nsanje which are located in the southern part of Malawi (Figure.1).

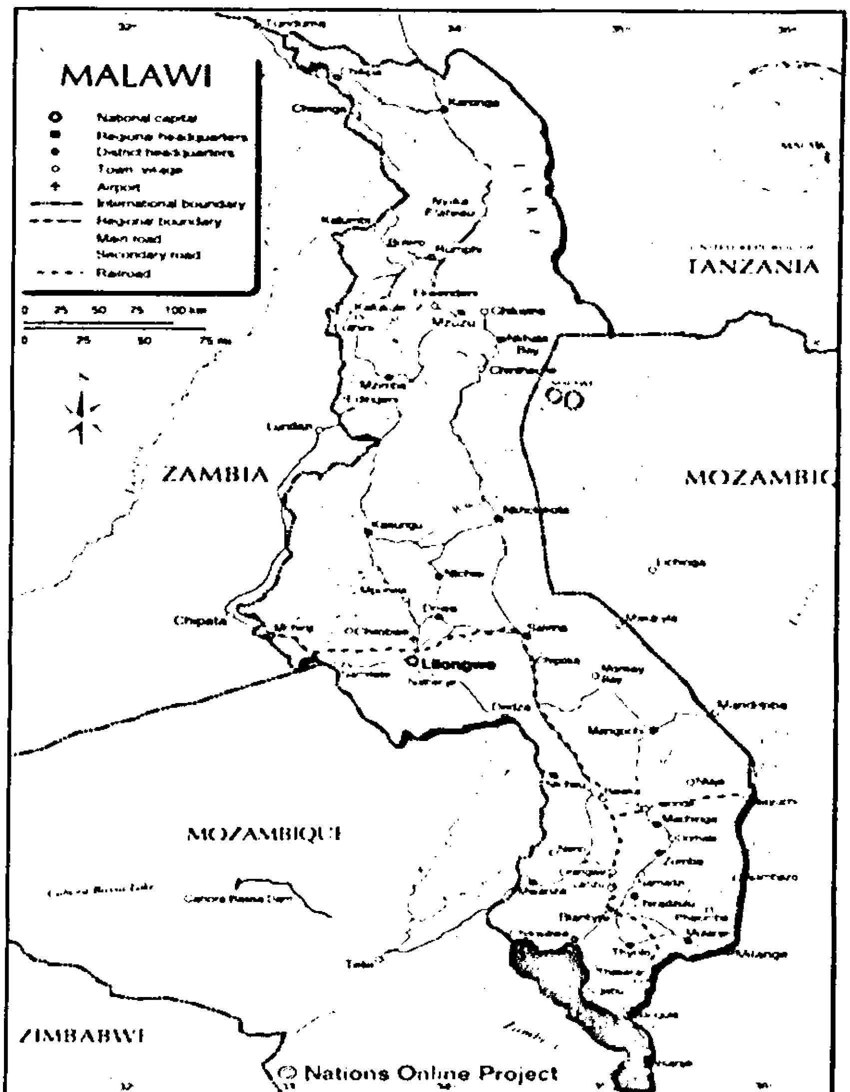


Figure.1: Map of Malawi showing Shire Valley in blue.
Source (*http//www.nationsonline.org/oneworld/map/malawi_map.htm)*

This area covers 6720km^2 with 2950km^2 consisting of national parks, game reserves, forest reserves and controlled areas. Some 630km^2 of land is under marsh while over 155km^2 is used by Illovo Sugar Company. The remaining land is available for settlement and cropping agriculture (*World Bank 1978; NSO, 2006*). The valley floor is an elongated alluvial plain, about 144 km long and the width is between 16km at the tip to 32km over the northern part. It lies between 34.27 to 35.32 °E and 15.84 to 17.14 °S at an altitude of 32-180m above sea level., (*Chilimba et al., 2011*). The Shire River flows through two marshes with extensive areas of hydrormophic soils. To the east of the river, up to Thyolo soils are medium to coarse textured alluvial and colluvial. To the west, there is a broad plain with vertisol and grey brown earths, rising towards the western escarpment (*Saka et al., 2003b; Chilimba, 2011*).

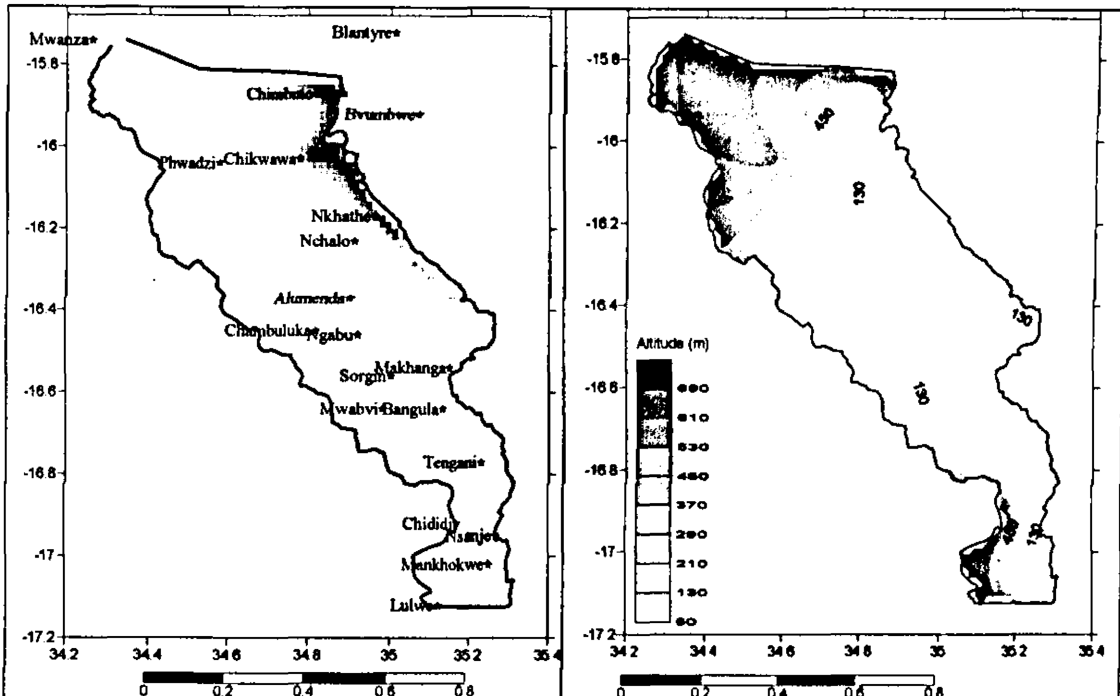


Figure.2(a): Rainfall and non rainfall stations in the Shire Valley

Figure. 2(b): Shire Valley Altitude in meters

Figure.2: Shows (a) the distribution of rainfall stations and (b) altitude (m) of the study sites

1.6.2 Climate of Malawi and Shire Valley

Malawi lies between the east and south east Africa regions and enjoy a sub-tropical climate with a quite unpredictable weather pattern (*GFDRR, 2011*). Climatologically the country is located between the two core ENSO regions (east African region which receives enhanced rainfall during positive ENSO phase and southern Africa region which receives enhanced rainfall during negative ENSO phase) making it even harder to predict the likely ENSO impacts (*Washington and Preston, 2006; Jury and Mwafulirwa, 1989*). Although weather is associated with south-eastern region impacts most of the years, influence of every ENSO event over Malawi weather is different. The climate is largely influenced by the huge water mass of Lake Malawi, which defines almost two-thirds of Malawi's eastern border. The dry period of the 1990's associated with the 1991 El Niño event is evident, (*Ann Bot, 2009*). The country has two distinct seasons, the rainy season from November to April, and the dry season from May to October. The dry season is further divided into the cool dry period and the hot dry period. A cool dry season is experienced during the middle months of the year (May-August), temperatures vary from 10 - 15°C in the uplands and 18-24°C in the southern valleys. In the central plain and northern highlands, temperatures can be as low as < 5°C during night. Cases of frosts can be reported in some isolated areas in the upper plateau, (*Malawi MET, 2004*). Mean temperatures in June a cool winter month is 24.3°C and for December a warm summer month is 28.6°C. A hot and dry season is between September and November where temperatures vary from around 16°C-35°C and can go up to 42°C in the valley. Being in the valley's extreme southern part, the area can experience a severe drought while the north is wet. Nearly all of Shire Valley's rains (over 90 percent) fall during the warm and wet season (November -April).

Although southern part of Malawi falls in the homogenous rainfall zones identified by its rainfall onset, the zone does not adequately describe rainfall patterns for Shire valley at the annual level. Rainfall in the area is poorly distributed and ranges between 400-600mm annually with mean temperatures of 35°C, (*Mwafulirwa, 2007*). Annual rainfall at this location varies greatly from year to year ranging from 400 to 650mm with a mean of 534 mm (1971–2000). On average, winter (May–September) and summer (October–April) rainfall accounts for 18.7% and 81.3% of the annual rainfall, respectively. In a single day, as much as 160mm of rains can fall resulting into severe flooding and can cause damages to infrastructure across the country as in 2008 (*ActionAid, 2008*). The trend of climate variability in the Shire Valley shows a general increase in minimum and maximum temperature and a decrease in mean rainfall for other months except January. These indicate that climate change effects are already affecting community's livelihoods in the area. Conversely, droughts also hit the country in some years, and Shire Valley is very prone to it as in 1991, (*MVAC 2005*).

Although OND and JFM are the official months for climate analysis in southern Africa, McSweeney analysis of Malawi data used December, January and February (DJF). In his assessment, he found out that temperature increase has been most rapid in the rainy summer (December-February) and lowest in the hottest season (September-November). In 2006, wet-season (December-February) rainfall over Malawi was markedly low, possibly causing a decreasing trend in December-February rainfall; however, evidence does not reveal consistent decreases. Mean annual air temperature is 34°C and mean temperatures for June and December were 24.3°C and 28.6°C, respectively. It is very difficult to identify long term rainfall trends in Malawi due to high year-to-year variability (*McSweeney, et al., 2008)*. In his study, McSweeney pointed out that a 2006 rainfall season for (DJF) was low, causing a decrease in DJF rainfall trend but lacks evidence of consistent decrease (*McSweeney et al., 2008*).

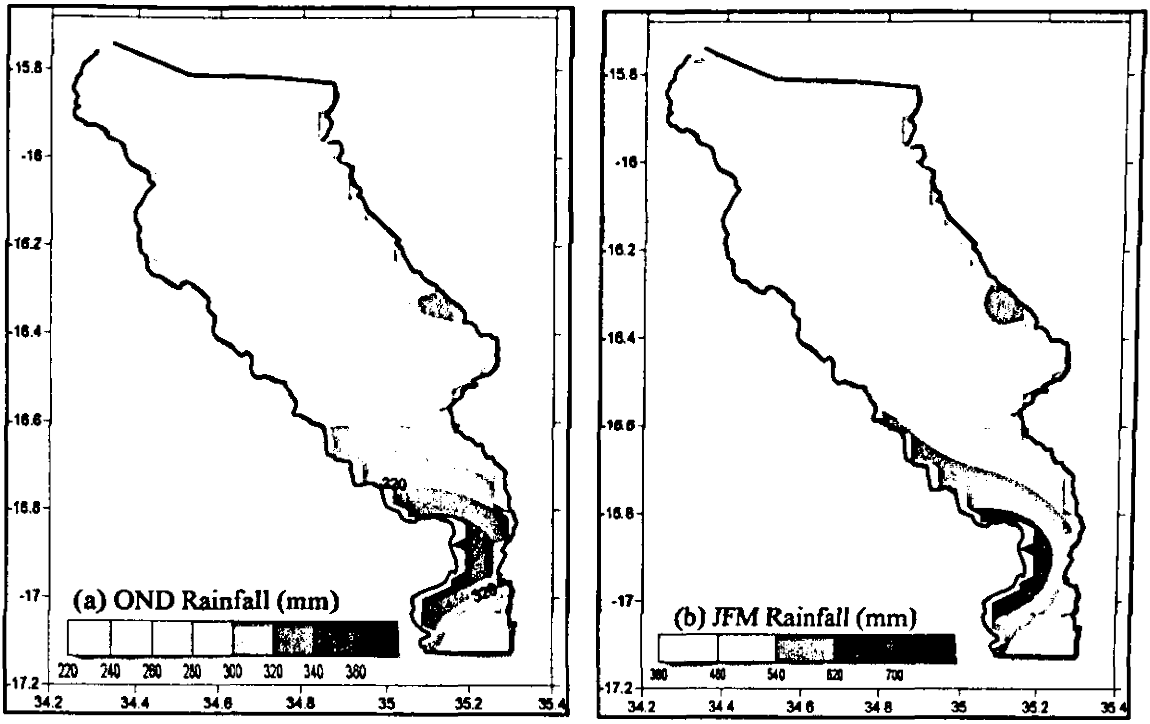


Figure 3: Map of Shire Valley showing (a) OND and (b) JFM mean rainfall distribution.

Shire Valley lies in the rain shadow due to the Shire highlands to the east and Kirk range to the west. Rainfall is poorly distributed with annual rainfall varying greatly from 400 to 650mm and a mean of 534mm (1971–2000). On average, winter (May–September) and summer (October–April) rainfall accounts for 8.7% and 91.3% of the annual rainfall, respectively [*ibid.*]. It is therefore important to understand how climate change will impact on the productivity of sorghum

CHAPTER TWO

2.0 LITERATURE REVIEW

This chapter presents a review of past and present activities, as well as the methodologies related to this study. The chapter starts by looking at climate variability and change at a broader scale then narrows down to country level in order to capture the local climatic situation of the Shire Valley of Malawi. This is followed by an extensive review of Sorghum growth and development in the light of the influences of environmental conditions. The chapter also reviews the past modelling efforts in the area of climate change projections and impact studies.

2.1 Climate change and its impact on agriculture production

Climate is a generalization of weather changes and is represented by a set of weather conditions in a given spatial area over a given time interval (*Gruza et al., 2004*). A statistical description in terms of means, extremes, variability indices for certain parameters, and frequencies of events over a given time period is used for climate characterization *[ibid.]*. As such any climatic variables can be used for scientific analysis of climate variability and changes, and any base periods including those different from 30 years can be used for estimating deviations from averages. Climate variability and change (CVC) is an important socio-economic and environmental issue. It is defined by (*Molla et al., 2011*) as a shift in the mean state of the climate or its variability, persisting for an extended period, decade or longer (or a continuous spectrum of changes in meteorological and oceanic characteristics, (*Gruza et al., 2004*). Climate variability affect the achievement of Millennium Development Goals (MGDs) aimed at poverty and hunger reduction, health improvement and environmental sustainability (*UNDP, 2010; NAPA, 2006*).

In the 21st century, severity and frequency of these weather extremes have been and would still be experienced over many areas around the world including Sub Saharan Africa (SSA), (*UNDP, 2011*). At lower latitudes, especially seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases (1-2 °C), which would increase the food risk *(Rai, et al., 2010)*. Results from various studies have predicted that there will be increase in frequency and magnitude of extreme weather under climate change (*Semenov, 2009, IPCC, 2007*). Changes in climate variability and extremes have received increased attention in recent years. Variability in a normally distributed parameter occurs when changes in the mean, the variance, or both cause the probability distribution to 'shift', resulting in changes in the frequency of occurrence of extreme events in either the upper or lower tail of the distributions

(Pancura and Lines, 2005). Variables that are not well approximated by normal distributions, like rainfall, are more complex, especially for dry climates (*Line, et al., 2005*). For rainfall, for example, changes in the mean total rainfall can be accompanied by other changes like the frequency of rainfall or the shape of the distribution including its variability *(Unganai, 1996).*
Most of the earlier studies have associated climate variability to outcomes such as yields, land values, and farm economical profits (*UNFCCC, 2007*). Climatic studies have focused on yields and emphasized in the influence of weather on the dynamic physiological process of plant growth and grain formation (*Tadros, et al 2009*). The studies also explore the use of theoretical model to simulate yields given daily weather inputs, nutrient applications, initial soil conditions and management practices (*Yang, et al., 2006*). Climate scenarios have also been used in most studies to assess the effect of a changing climate on various crops (*Rowhani et al, 2011*). By incorporating these scenarios into the crop models in some cases, the simulated yields compares to observed yields with remarkable success. For this reason, climate variability and change studies have become a focal point of crop diversification around the global (*Mullera et al., 2011*).

Most model simulations indicate that sustained radiative forcing following a doubling of CO_2 concentrations will increase global average surface temperatures by between 2°C to 4.5°C, with a best estimate of about 3°C (*Mathews, et. al,. 2007*). Some global climate models (GCM) simulate increased summer dryness and winter wetness over most parts of the global including sub Sahara Africa with an increased chance of intense rains over Southern Africa due to the greater water-holding capacity of a warmer atmosphere resulting into flooding (*Knox et al. 2006*). Evidence from the Intergovernmental Panel on Climate Change is now overwhelmingly convincing that climate change will hit the poorest and most vulnerable people seriously (*IPCC, 2007*). The *IPCC (2007)* also concludes that future tropical cyclones (typhoons and hurricanes) will likely become more intense, with larger peak wind speeds and more heavy rainfall associated with ongoing increases of tropical SSTs.

Institutions such as Food and Agricultural Organization (FAO), the International Fund for Agricultural Development (IFAD), World Bank, and others acknowledges climate change as one of the challenges they need to address because of how it affect rural poverty. Although it is a global phenomenon, its negative impacts are more severely felt by poor people in developing countries who heavily rely on the natural resource base for their livelihoods (*ICRA, 2009*). Agriculture, amongst the most climate-sensitive economic sectors, is more exposed to the effects of climate change hence affecting the rural poor communities. Prediction by IPCC shows that by 2100 a global average surface temperature increase may be between 1.8 and 4.0°C while with a global average temperature increases of only 1.5–2.5°C degrees, there is high extinction risk of animal and plant species by approximately 20-30% (*FAO, 2007*). Coupled with slow technological and economical growth, the effects of such change would put Malawi animals and plant species at greater risk.

For Malawi, mean annual temperature is projected to increase by 1.1 to 3.0°C by 2060's and by 1.5 to 5.0°C by the year 2090s (*GFDRR, 2011*), thereby posing a high extinction risk of animal and plant species by approximately 20 to 30 % (*FAO, 2007*). The study by GFDRR using 1961-1990 as baseline while projecting at high and low scenarios have shown that climate change impacts will vary for different crops in Malawi. Sorghum was projected to change by 4.38% in the 2010s, 1.67% in the 2050s and 3.19% in the 2080s while Maize will change by 4.67 to11.65% between 2010 and 2080.

Studies to determine whether there is evidence of climate change in climate data series have been done on a variety of long time series weather observations from across the world (*WMO, 2000*). Several analyses have been performed on temperature, rainfall and river flows and lake levels. Up until recently most GCM models running climate change experiments have dwelt on potential changes in climatic averages. Some authors, notably *Katz et al (1992),* have argued that variability is more important than averages when assessing the impacts of climate change, since the primary impact of climate change on society results from extreme events. According to (*WMO, 2000),* there is no conclusive evidence of a climate change signature. Findings reported in specific works cannot be generalized and to a large extent appear to be localized chance occurrences. These studies found diverse results with the impacts of temperature increases and rainfall changes varying markedly across different parts of Malawi, (*Hewitson et al. 2006).* Although little is known about the impacts of climate variability on yield reductions in this region, the authors mostly emphases on a high likelihood of significant yield reductions.

Impacts of climate variability and change on sorghum production in Malawi were studied by (*Tadros, et al., 2009*), who concluded that large declines in cereal yields were likely to occur by 2030. They therefore recommended regional adaptation strategies such as developing drought resistant cultivars, water conservation measures, using and adjusting planting dates and crop choice in order to mitigate likely impacts. Model results estimate that droughts over Malawi, on average, cause GDP losses of almost 1 percent every year and economic losses are much higher during extreme droughts (*GFDRR, 2011*). One study suggests a possibility that rainy seasons will grow shorter, potentially leading to more frequent failures in maize cultivation, which in turn has significant implications for future food security (*Tadros, et al, 2009*). Irrigation proves to be the best option of mitigating recurrence of droughts and other impacts of climate change.

However, such adaptation strategies are likely to be site-specific, depending on terrain, soil type, and methods of water use, among many others.

To cope with recurring floods, potential interventions should focus on the construction of flood protection structures. Studies on climate variability for Malawi established that mean annual temperature has increased by 0.9°C between 1960 and 2006, an average rate of 0.21°C per decade (*GFDRR, 2011*). The average number of 'hot' days per year in Malawi has increased by 30.5 between 1960 and 2003. The average number of 'hot' nights per year increased by 41 nights, 11.1% increase between 1960 and 2003 [*ibid.*]. The frequency of cold days and nights has decreased significantly since 1960 in all seasons except September-November (*McSweeney, 2008*).

2.2 Climate Change and Sorghum Production Trends

Sorghum is a food crop predominantly grown in Shire Valley, with 55% of the total area prepared for crop production (*MVAC, 2010*). Area for planting sorghum has been increasing gradually over the last five years but productivity has been around 0.8 MT/ha in the last four years (*FEWSNET, 2008*). The lack of plausible change in harvested yields, however, was due to the outdated crop management practices, prolonged dry spells and frequent droughts in the area where 68% of the crop is grown. As sorghum is a drought-tolerant grain with a strong adaptive advantage and lower risk of failure than other cereals in such environments, the loss has not been severe. The year to year yield variation in the area was attributed to climate variability such as dry spell, floods and drought (*UNCEF, 2008*). Cropping practices, technology and in comparison to maize, preference are additional reason for constant yield. With already visible climate variations (dry spells and droughts), it is expected that climate change will bring mixed results for sorghum which would include a decrease in quality due to pests and diseases (*Rowhani et al., 2011*). Variations in these indices were calculated to find trends using daily rainfall data and these variations were linked to large-scale climate modes after correlated to ENSO (*Tadros, et al., 2009*). The southern oscillation phenomenon (ENSO) phenomenon is the primary driver of inter-annual climate variability and has a large economic and social impact over the universe (*Glantz et al., 1999*). *Fedorov* and *Philander,(2000)* showed that mean fluctuations of decadal timescale do contribute significantly to the later unusual ENSO events and suggested that global warming cannot be ruled out as a suspect *Glantz et al., (1999).* El Nino-like differences can be found in the projected results by the AGCM under global warming, (*Wu et al., 2001).*

Few studies of the specific impacts of climate change on Malawi sorghum cropping systems have been done to date. Most of these studies were centred on the assessment of the effects of a changing climate on maize and sorghum cropping systems in Malawi (*IFPRI, 2009*), changes in sorghum yields and grain quality at Kasinthula and Ngabu sites in Malawi [ibid.]. However, few or none of these studies used sorghum model, in conjunction with GCM outputs although reductions in rainfall due to climate change are likely known to limit future sorghum production (*Rowhani, et al., 2011*). In study done on maize, observed changes in daily rainfall records were used to evaluate the agricultural implications climate variations by calculating indices that were directly related to farm management decisions and impacts on crop growth (*Tadros et al., 2009*). The study findings were that impact of rainfall variability on maize production is clearly tied to the planting date and timing with respect to the crop phenological phases. Since sorghum is grown in regions that experience high rainfall variability during the key growing months, November to April period (*MVAC, 2010*), increase in rainfall variability and extreme events due to climate change (*McSweeney, 2008*) will further affect production. Any drop in subsistence crop production result in the scarcity of its supply and pushes the market prices up. Continual crop failures over Shire valley have led most farmers to mixed farming. According to *Kabubo-Mariara, (2008)* and *Munthali et al,.(1989)*, livestock production is a choice of household's resource allocation and a livelihood diversification strategy to avoid persistence of crop failure. Regardless of the above points, history had revealed that millet and sorghum production was a staple food for Malawi but urbanization has shifted people's preference to maize, rice and other crops. This has been and is still evident through agricultural policies which are biased towards other crop production particularly maize. Thus, as a nation there is an urgent need to initiate and develop policies (institutional and macroeconomic) that are favourable for increasing adaption mechanisms of sorghum production (*NAPA, 2006*).

The country's exposure to climate change and extreme weather events has been identified through various studies including the state of the environment report for Malawi 1998, the Initial National Communication to the *UNFCCC, (2002)* and Malawi National Strategy for Sustainable Development (2004). The 2002 Vulnerability and Adaptation Assessment Report indicated that Malawi is experiencing a range of climatic hazards, which include extreme rainfall, floods, seasonal and multi-year droughts, dry and cold spells, strong winds, thunderstorms, landslides, hailstorms, earthquake and mudslides, heat waves, and many others. Over the last decade, Shire Valley, through which the Shire River flows, has experienced some of the worst droughts (1991/92) and floods (2000/01) in living memory (*NAPA, 2005*). The impact of these events resulted into low agricultural production, consequently hunger, malnutrition, loss of human and animal life and other socio-economic and industrial activities.

A research done at ICRISAT-Zimbabwe using the suggestion of IPCC under A1B green house gas emission indicated that southern Africa will experience average annual temperature increases of 3.1°C and changes in annual rainfall of between -12 and +6%. Atmospheric carbon dioxide levels for this scenario are expected to increase to around 700ppm from the current 370ppm, *(John Dimes et. al, 2008)*. Through the use of the long-term daily climate data (1951–2001), the research looked at positive (CO_2 fertilization) and negative (higher temperature, lower rainfall) impacts of these projected climate changes on crop productivity using the crop systems simulation model APSIM with its climate change module, (*McCarthy, et al., 2009*). However, for Malawi, research gap on climate change impacts on agriculture sector exits particularly in sorghum production.

Some studies done by ActionAid have shown that by 2100, Malawi will be severely crippled by the effects of climate change (*ActionAid, 2008; UNDP, 2011*). The effects will be felt very much in the agricultural sector where over 90% of the population is engaged in. Coupled with population pressure and declines in the arable land, Malawi's temperatures are predicted to increase by 1°C in 2020, 2°C in 2075, and 4°C by 2100 while over highlands rainfall will increase by 2 to 8% in 2100, (*ActionAid, 2008; McSweeney, et.al. 2008 and Tearfund, 2010*). With these increases, drought and floods are expected to increase with a negative impact on food production in Shire Valley. IPCC also identified agriculture as the most affected sector of economy, with production projected to reduce by 50% by 2020. For this reason agricultural activities have become a focus of modelling the impact of climate change on poverty and people livelihoods (*Dorward, et al., 2004*).

Models such as APSIM have extensively been tested on sorghum, maize, rice, and wheat growth and yields, soil water balance and summer soil water dynamics in arid regions of East/West Africa, China, India and Australia wheat belt (*Keating et al., 2003*) and found robust. In carbon fertilisation studies conducted using APSIM sorghum model, results shows that increasing CO_2 concentrations will increase crop yields by around 6–8%. Another study conducted by *(Reeves et. al., 1994)* has shown that elevated CO_2 increased total dry matter production of sorghum by 14.4% while increased carbon (C) fixation and resultant dry matter production was not sufficient to alter the CN ratio of sorghum leaf tissue. According to Humphreys, (*Humphreys et al., 2008*), this suggested that nutrient status of field grown sorghum is not greatly affected by increased atmospheric CO_2 concentration.

Reduced rainfall is expected to negatively impact sorghum yield in the future. However, it is increase in temperature that has the most dramatic impact on grain yields and not reduced rainfall; reductions of 16% for the two cereals. A combined effects of climate change will reduce sorghum yield by 22%, and 25% reduction on maize (*Cooper et. al., 2 009; Ainsworth et al., 2010*). In a related study, *Robinson et al.,(2006)* found out that climate variability will affect management practices of various agricultural activities by influencing weeds growing mechanisms. Understanding responds of plants species, particularly sorghum to changes in temperature and rainfall regimes will help in predicting shifts in plant communities and pest species management.

2.4 Sorghum Production

2.4.1 Importance of Sorghum in Africa

Sorghum (*Sorghum bicolour* [L.] Moench) is an indigenous crop to Africa. It is a wonderful crop species that produce livelihood for producers in areas (semi-arid tropics of Africa and Asia) too dry for other grain crops (*FAO, 2007*). It is fifth in the world and seconds in southern Africa and has gained increasing importance as a fodder (green/dry) and feed crop in the last decade (*ICRISAT, 2004a*) and compete with maize under irrigated culture because of oats productivity and short season requirement, *(Cameron, 2006).*

In the competitive environment of multi-national enterprises, sorghum has been proven to be the best alternative to barley for lager beer brewing. Studies on the economic benefits of the different cereal grain crops found sorghum as a major income earner for some countries, including Nigeria, Sudan and Ethiopia. According to *DeWalt, et al., (2002)*, this crop is only being grown in specified parts of the world; other countries like the United States and Great Britain import the grain, which benefits the exporting countries. Major producers in the world are United State of America where sorghum is used as feed, India, Nigeria, Mexico, Sudan and Argentina where it is mostly grown as food *(Wayne et al., 2000).* On balance, sorghum will remain a key food security crop in Africa for the foreseeable future. Productivity gains are essential to offset the prospects of continuing food production shortfalls in most semi-arid regions and the prospects of periodic famine in some. Since most sorghum is still grown by poorer small-scale farmers, investments in research and extension will contribute directly to poverty alleviation *(Kleih et al., 2007).*

2.4.2 Sorghum Production in Malawi and in the Shire Valley

In Malawi, sorghum is a major cereal crop, and was originally a staple food for the country (*Ngaiyaye, et al., 2008*). Marginalization of the crop came about with the introduction of maize due to its poor digestibility. Sorghum is mainly cultivated in drier areas, especially on shallow and heavy clay soils. Its productivity varies annually depending on the previous year's drought impact and preference (*Ngaiyaye, et al., 2008*). Although sorghum is extensively grown in the Shire Valley region where it remains the basic staple food (*MVAC, 2005*) in recent years, there has been a shift in its production from the drier southern production areas of the shire valley to the wetter eastern highlands of the Shire highlands. Although Shire Valley region is the largest producer of sorghum, this has led to the identification and development of other cultivars which are more tolerant to lower temperatures (*ICRISAT, 2004b*). The crop is suitable if grown under water stressed, low fertility and high temperatures areas. It is a drought resistant and a fast maturing crop that develops so quickly (*Hazeltine, 1998*). It utilizes any moisture stored in the relatively shallow soil layers and has the capacity to recover from drought stress and resume growth (*ICRISAT, 2004*). The yield under these circumstances is often reduced, but some recovery is made when moisture comes. Sorghum if exposed to severe moisture shortage and high temperature over a prolonged period, although it will not result into plant death, its recovery will be insufficient to produce economic yields when moisture returns in the soil *(Vanderlip 1993).* In a research conducted at ICRISAT-Zimbabwe and Kenya, it was found that sorghum experience greater shortening of the vegetative phase (18%) relative to the grain filling phase (14%) resulting into increasing averaged harvesting index (HI) while retaining a water use efficiency (WUE) of 6.7kg ha^{-1} mm^{-1}, (*Dimes et al., 2009*). The result was a low yield high HI which contributed to low biomass. Sorghum like maize on the other hand, shows varying degrees of drought resistance. Under the combined effect of climate change, all crops shows large reductions in days to maturity (13-18%) and reduced biomass(18-27%) except pigeonpea, *(Dimes et al., 2009).* A range of climate studies have shown that grain proteins in cereals like sorghum decreases in response to combined effect of climate and carbon dioxide (*Crimp, et al., 2008*).

With the simultaneous increase in the production maize, sorghum faces competition from the utilization point of view. Already there is an increasing trend of using maize in place of sorghum even in areas where sorghum had been a traditional staple food in the past (Taylor, 2002). However due to climate change, sorghum will remain a major food crops in Malawi, particularly the Shire Valley where maize failure is common.

Figure.4: Maize crop that has failed due to drought.
Source *MVAC report, 2010*

2.5 Sorghum Morphology, Growth and Development

2.5.1 Growth and development

Sorghum belongs to the grass family called *Graminea.* It is essential that producers know the crop they are cultivating in order to develop the most effective production practices. The growth and development of sorghum are divided into the vegetative and reproductive growth stages. Vegetative growth stage is identified by leaf development while a reproductive growth stage is typically identified by the development of grain kernels.

Figure 5: Sorghum crop under rain fed environment.
(Source UK Cooperative Extension Services)

2.5.2 Root and Leaves

The roots of the sorghum plant is divided two parts, primary and secondary system. The primary roots appear first and provide the seedling with water and nutrients from the soil but have limited growth as their functions is taken over by the secondary roots (*Saberi, et al,.2011*). Secondary roots develop from nodes below the soil surface and branches freely, both laterally and downwards into the soil. They can reach a lateral distribution of 1m and a depth of up to 2m early in the life of the plant. They are finer and branch approximately twice as much as roots from maize plants (*Jéan du Plessis 2008*). It has deep roots that help the plant to be drought tolerant *(Norman Borlaug, 1996)*. Leaves of Sorghum are green, flat, solid and dry, stems are storage of sugar to sustain the plant growth as such, they are succulent and sweet (*House, 1985*). Leaves are long, narrow and have pointed blades with area smaller than that of maize (Figure.4b), the leaves are covered by a thin wax layer which reduces transpiration and increases the drought tolerance of the plant (*Carter, 1989*). Stomata occur on both surfaces of the leaf, (*Jéan du Plessis 2008*). Number of leaves and may vary from 8 to 22 leaves per plant depending on environmental conditions. Motor cells exist in a row along the midrib on the upper surface of the leaf and they rapidly rolls up the leaves when there is moisture stress during the crop growth. (*Vanderlip, 1993*)

2.5.3 Flowering and pollination in Sorghum Plant

The flowers of sorghum open during night or early morning; those at the top of the panicle open first and pollinates soon after panicle has completely emerged from the boot, (*Carter, 1989*). It takes approximately 6 to 9 days for the entire panicle to flower. Sorghum is mainly self-pollination and, pollination normally occurs between 200 and 800 a.m. and fertilisation takes place 6-12 later. Pollen shedding begins at the top and a small percentage of cross-pollination (approximately 6 %) occurs naturally (*Carter, 1989*). Pollination is highly affected by increase in temperature leading to infertility. A study done by *Vara Prasad et al.,(2006)* showed that high temperatures decreases both pollen production and reception of pollen by stigma leading to lower spikelet fertility and fewer filled grains. During inflorescence of sorghum, the panicle may be compact or open. The peduncle is usually straight and its length varies from 75 to 500 mm (*Blade, 2010*). Each panicle contains from 800 to 3000 kernels which are usually partly enclosed by glumes. The colour of the glumes may be black, red, and brown or tan (*Jéan du Plessis 2008*).

2.5.4 Climate and Soil requirements for Sorghum

Sorghum tolerates a wide range of climatic and soil conditions. The climatic requirements for the production of sorghum are divided into temperature, day length and water needs.

2.5.4.1 *Rainfall*

Apart from being more heat and drought resistant than maize, sorghum plant can also withstand periodic water logging without much damage (*Hazeltine et al., 2003*). Sorghum is best adapted to areas having an average annual rainfall of between 450 to 750mm although it can respond well to soil moisture. It is the most tolerant crop to floods at all growth stages in term of grain yield, *(Zolezzi, et al., 1978)*. However, studies have shown that rainfall, relative humidity and their seasonal variability are some of the most significant factors than affects sorghum yield *(Adamu Ibrahim et al,. 2006)*. According to *Adamu Ibrahim et al, (2006)* in 1977, Niewwolt reported that plants can absorb moisture directly from the air and the rates of photosynthesis generally increase with relative humidity. This shows that in areas where relative humidity is very low crop yield is reduced due to poor photosynthetic process.

2.5.4.2 Relative humidity and crops

Plant development depends on high atmospheric humidity in the sense that many plants have the ability to directly absorb moisture from unsaturated air of high humidity. Humidity may again affect the photosynthesis of plant leaves. High humidity at night is beneficial to some plants, *(Tunde, et al,.2011)*.

2.5.4.3 *Temperature*

Sorghum is a warm-weather crop and requires high temperatures about 26-30°C for good germination and growth. Temperature plays an important role in growth and development after germination. Minimum germination temperatures vary from 7 to 10 °C and at about 15 °C, 80 % of seed germinate within 10 to 12 days (*Patane, et al., 2009*). Soil temperature strongly influences both percentage germination and time of emergence of sorghum (*Kanemasu, et al,. 1975*). *Kanemasu* further reported that sorghum require optimum germination temperature of about 23°C and a heat requirement of 67 degree days. Poor emergence and seedling growth may result if planted before soil temperatures reach 35°C. The best time to plant is when there is sufficient water in the soil and the soil temperature is 15°C or higher at a depth of 10 cm. A temperature of 27 to 30°C is required for optimum growth and development. The temperature can, however, be as low as 21°C, without a dramatic effect on the growth and yield crop, (*FANRPAN, 2010*). Low temperature, not length of growing season, is the limiting factor for production (*Carter, 1989*). Exceptionally high temperatures cause a decrease in yield. Warmer air temperatures accelerated plant phenology, reducing dry matter accumulation and crop yields by 10–40%, (*Tubiello et al., 2010)*. Flower initiation and the development of flower primordial are delayed with increased day and night temperatures. During the period from panicle initiation to anthesis that high temperature leads to reduction in the grain yield of sorghum through its shortening of the period of panicle development *(Peacock and Wilson, 1984)*. Sorghum does not germinate and grow well under cool soil conditions. Temperatures below freezing are detrimental and may kill the plant. At an age of 1 to 3 weeks, plants may recover if exposed to a temperature of 5°C below freezing point, but at 7°C below freezing, plants are killed. Frost will generally kill the top of the plant and help to lower the moisture content *(Carter, et al, 1989).* Plants older than 3 weeks are less tolerant to low temperatures and may die off at 0°C. *Downes (1972)* pointed out that air temperatures >30°C during vegetative stage delayed floral development, particularly initiation of panicle meristem. Therefore, the vegetative phase became longer than usual and the grain yield was reduced

2.5.4.4 *Day length*

Sorghum is one of the most photosynthetically efficient plants and has the highest dry matter accumulation rates. It is the fastest maturing food plants (certain varieties can mature in as little as 75 days and can provide three harvests a year) *(Norman Borlaug, et al., 1996).* Sorghum is a short-day plant, which means that the plant requires short days (long nights) before proceeding to the reproductive stage. It is more sensitive to photoperiod during flower initiation. The optimum photoperiod, for inducing flower formation, is between 10 and 11 hours and beyond these hours (≥12hours) stimulates vegetative growth *(Folliard, et al., 2004).* The tropical varieties are usually more sensitive to photoperiod than the quick, short-season varieties. Rate of growth is largely determined by the net photosynthetic rate of the leaves and panicles. *Escalada and Plucknett, (1975)* found that sorghum matures early with higher temperature and shorter day length. He further noted that low light intensity, short photoperiod, and low temperature, resulted in rosette form of foliage with very short internodes and reduced number of leaves which led to low grain yields.

2.5.4.5 Photosynthetic advantage of sorghum over C3plants.

Sorghum is a tropical efficient C4 plants (Calvin cycle), this means light, temperatures and day lengths are the controlling or limiting factors, *(Wayne et al, 2000).* A photosynthetic pathway called C-4 photosynthesis gives sorghum a competitive advantage over C-3 plants during hot summer days. In ordinary C-3 plants which form a 3-carbon compound (PGA) during the initial steps of the dark reactions, photosynthesis in the leaf shuts down without a sufficient supply of CO_2. During hot weather the CO_2 level inside leaves is greatly reduced because the leaf stomata are closed *(Ehleringer, et al., 2002).* In C-4 plants, CO_2 combines with phosphoenolpyruvate (PEP) to form a 4-carbon organic acid (oxaloacetic acid) which migrates (diffuses) to the photosynthetic bundle sheath cells surrounding the vascular bundles (veins) of the leaf. PEP essentially carries the CO_2 to the bundle sheath cells where it is released for the dark reactions (Calvin cycle) of photosynthesis *(Ehleringer, et al., 1997)*. Sorghum is able to carry on photosynthesis in the bundle sheaths where CO_2 levels are concentrated. The oxygen liberated during the light reactions of photosynthesis comes from water. As a result, C-4 plants photosynthesize and grow rapidly during hot summer days than their counterparts, C-3 plants which shut down their stomata. Nevertheless, under elevated CO2 environments or at cool temperatures, the efficiency of photosynthesis is greater in C3 photosynthesis because photorespiration is reduced and the additional ATP cost of C4 photosynthesis makes it less efficient, *(Ehleringer, et al., 2002).*

2.5.4.6 *Water requirements*

Sorghum is produced in Malawi on a wide range of soils, under fluctuating rainfall conditions of approximately 400 mm in the drier western parts to about 800 mm in the wetter eastern parts. Although crop water required mainly depends on climate; for example in a sunny and hot climate, crops need more water per day than in a cloudy and cool climate and crop type. Sorghum crop growth stages are the one critical to water stress; fully grown crops need more water than crops that have just been planted (*FAO, 2009*). However, at equal moisture stress, maize leaves lose a more of their water content than sorghum leaves because of the waxy coating on sorghum leaves and stems.

Table 1 Crop water Requirement.

Crop	Growing period in days	CWR (mm)/ growing period
Maize	90 - 140+	500 – 700
Sorghum	90 - 140+	450 – 650

Source; FAO

2.5.4.7 *Fertility requirement for sorghum*

Sorghum is mainly grown on low potential, shallow soils with high clay content, which usually are not suitable for the production of maize. It grows poorly on sandy soils, except where heavy textured subsoil is present. The crop is more tolerant of alkaline soils than other grain crops and can therefore be successfully cultivated on soils with a pH (*KCl*) between 5.5 and 8.5 (*Uchida and Silva, 2000*). Sorghum can better tolerate short periods of water logging compared to maize (*Saberi, et al,.2011*). Soils with a clay percentage of between 10 and 30 % are optimal for sorghum production. Although sorghum does well in low fertility soils, ongoing development of a high-resolution digital soil map of Africa would enable farmers to exactly know the forms of mineral and organic fertilizers required in each field *(Sanchez, 2010).* This would results in optimizing crop production in the area.

The ratio of carbon to nitrogen is the carbon nitrogen ratio (C:N ratio). The C:N ratio of the organic material added to the soil influences the rate of decomposition of organic matter and this results in the release (mineralization) or immobilization of soil nitrogen *(Kleih et al, 2007).* Fertilizer is annually added to the soil through the natural process such as combustion, decomposition and lightning (acid rains). Total nitrogen input from atmosphere 5-60kg/ha per year depending on the pollution of the air. In another study, total deposition of nitrogen on bare soil is 37kg/ha and about 48 kg ha/year on the soil with a well-established crop of winter wheat, *(Addiscott, 1992).* Addiscott further noted that on larger surface area difference in solar reflection also offer larger deposition by the crop. It is also observed that leached nitrogen deposition contributes to over percentages of 15% of the nitrate leached. It may thus contribute 10-15 kg/ha to annual nitrate losses from soil *[Ibid.]*. Therefore an adequate and balanced supply of plant nutrients is a prerequisite to maximize crop production. In regions of low rainfall, sorghum should be manured with 25t/ha compost and covered by means of blade harrow. The recommended inorganic fertilizer rates for sorghum crop are nitrogen (30kg/ha), phosphorus (40kg/ha) and potassium (20kg/ha) *Kaizzi et al.* available at (http//webapp.ciat.cgiar.org/tsbf_institute/pdf/theme_2.pdf). Sorghum requires a medium to good and fairly stable rainfall pattern during the growing season, moderate to warm weather (20-30°C) and a frost-free period of approximately 90 to 140 days, (*House, 1985*). The physiological maturity of sorghum is within 90 to 120 days and depends on the temperature and variety of sorghum grown (*Hazeltine et al., 2003*).

2.5.4.8 *Drought tolerance*

Sorghum is able to tolerate drought better than most grain crops and it resists drying. This can be attributed to an exceptionally well-developed and finely branched root system, which is very efficient in the absorption of water (*Blade, 2010*). Sorghum has a small leaf area per plant, which limits transpiration. The leaves fold up more efficiently during warm, dry conditions than that of maize. It has an effective transpiration ratio of 1310, as the plant uses only 310 parts of water to produce one part of dry matter, compared to a ratio of 1400 for maize. The epidermis of the leaf is corky and covered with a waxy layer, which protects the plant form desiccation (*Cameron, 2006*). The stomata close rapidly to limit water loss. Sorghum has massive and deep-penetrating roots which are responsible for its drought tolerance. It can conserves moisture by reducing its transpiration when stressed by rolling its leaves and closing the stomata to reduce evaporation. It also turns down its metabolic processes and retreat into near dormancy until the return of the rains *(Borlaug, et al., 1996)*. During dry periods, sorghum has the ability to remain in a virtually dormant stage and resume growth as soon as conditions become favourable. Even though the main stem can die, side shoots can develop and form seed when the water supply improves.

2.6 Management Practices

2.6.1 Land preparations, method of planting and rate of Seeding

In the Shire valley, method of planting as practiced by farmers is not documented. Land preparation for sorghum is done in similar way as for maize. For both varieties of sorghum, early land preparation before the rains is important. The crop does well in fine soils and can also be grown under minimum tillage conditions where the land is not ploughed.

Planting of sorghum is done at the beginning of the wet season. Seeds are planted along the furrows and put at 3 cm deep when dry planting to avoid germination in false rains. The row width used to plant depends most likely on the equipment available. Grain sorghum when planted in narrow rows boost grain yields (*Blade, 2010*). The spacing for dual purpose varieties allows for higher grain to herbage ratio. A drill by a hoe or the sore of the foot is used to plant the seeds in narrow rows. When the soil is wet, it can be planted at 2 cm deep. Sorghum is thinned when it is 30 cm high or 30 days after planting to ensure a spacing of 75 X 10 cm between rows for fodder sorghum and 60 X 20 cm between rows for dual-purpose varieties, (*Carter, et al,. 1989*).

2.6.2 Methods of Weeding, Diseases and Pests and their control

Hand weeding is the most common practice among local farmers and should be done at least twice. A weed-free field is required for sorghum especially at early stages of growth. Sorghum is generally disease tolerant but leaf diseases that exist in high rainfall and humidity areas can be problems although they do not cause serious losses. Planting resistant hybrid has proved to provide optimum growing conditions and minimize losses from diseases, *(Blade, 2010)*. Grain sorghum is resistant to corn rootworms, but may be attacked by corn earworms, aphids, and green bugs. As such control of cutworms, aphids, shoot-fly and stalk borer is important, *(Carter, et al., 1989)*.

Under Shire valley conditions, the most serious pest problems for grain sorghum growers are bird damage. Birds like sorghum especially at milk stage; they prefer white-seeded varieties than the red and brown. Planting early maturing crop and in areas far away from urban center can also reduce infestation by birds.

2.6.4 Harvesting

Grain sorghum is harvested as a standing crop by cutting the head. Where the crop is grown for commercial and in large quantities combiners are used. Sorghum grain is threshed free of the head when the seed moisture is 20-25% (*Carter, et al., 1989*). Some hybrids have a loose, open type head which hastens field drying. Sorghum seed is easily damaged in the threshing operation, especially when the grain is dry. The grain sorghum crop can be harvested for high-moisture grain silage. When fed to livestock, its digestibility will be increased by grinding or rolling. High moisture grain sorghum can be combined and ensiled when the grain is about 25-30% moisture, *(Blade, 2010)*.

2.6.5. Drying and Storage

Grain sorghum can be dried in any kind of equipment. However, because of the smaller grain size yield loss can be great if proper care is not taken. The grain sorghum need to be drier than maize for safe storage since there is less air movement through the finer grains. Grain should be stored at 13% moisture and in clean bins. In case of a drying process where heat is used, temperature should not be beyond 90°C since feeding values are reduced by high temperature *(Carter et.al., 1989)*.

2.7 The Agricultural Production Systems Simulator (APSIM)

2.7.1 APSIM Model Description

The Agricultural Production Systems Simulator (APSIM) is a crop modelling environment and it uses diverse modules to simulate cultivating systems in the semi-arid tropics. It is an effective tool for analyzing whole-farm systems, including crop and pasture sequences and rotations, and for considering strategic and tactical planning. The diverse modules are composed of biological, environmental, managerial and or economic which are linked together via the APSIM engine (*McCown, et al., 1996*). APSIM model is able to simulate the growth (leaf area index and biomass) and yield of a variety of crops (maize, soybean, chickpea, lucerne, sorghum, sugarcane, cotton, hemp, weeds, millet, cowpea, sunflower, etc.) in response to mixing crops, changing management practices and rotation sequences, as well as that for pastures and livestock (*Keating et al. 2003*). It is very flexible and can simulate short as well as on long term effects; allowing users to understand the long-term trends in soil productivity due to climate variability, fertility depletion and erosion. Details of scientific based information on simulation approaches employed for all functional components within APSIM are available on the Google APSIM forum and APSIM web sites http//groups.google.com/group/apsim/msg/; http//apsim.wikispaces.com/tag/view/apsim+help). Biophysical effects of these climate changes on agricultural production respond differently for various agricultural systems and regions (*Parry et al., 2004*). Projected changes in yield are calculated using transfer functions derived from crop model simulations with observed climate data and projected climate change scenarios (*Shin, et al., 2009*). The most important part of APSIM model is its ability to help users improve the understanding of the impact of climate, soil types and management on crop [*ibid.*]. However, the limiting factor of APSIM is its failure to deal directly with effects of salinization, insects, diseases or biodiversity loss. The crop modules available are for sorghum, maize, millet, and others. They have evolved from early versions for focus crops such as maize, peanut sorghum and sunflower (*Hammer et al., 1995*). The plant modules simulate key underpinning physiological processes and operate on a daily time step in response to input daily weather data, soil characteristics and crop management actions. The sorghum module in APSIM is not capable to respond to increased carbon dioxide levels other than legumes which modify the transpiration efficiency coefficient and the N concentration optimum for photosynthesis (*Dimes, et al., 2008*). Otherwise, it contains modules that permit the simulation of crop - weed interactions, soil organic matter rundown, nutrient leaching, soil erosion, soil structural decline, acidification and soil phosphorus.

2.7.2 APSIM Model Data Requirement

APSIM model is a flexible tool that requires site data comprised of latitude, soil texture and depth, slope length, *climate data* (daily max and min temperature, solar radiation and rainfall), crop phenology (crop type and cultivar, days to flowering, days to maturity), *Soil water, N and P* (soil moisture contents per layer at drained upper limit and lower limit, NO_3-N, soil carbon per layer, total soil N of the top layer contents NH_4 and NO_3-N and available P of manures, percentage groundcover for surface applied materials, soil bulk density per layer, P-extractable and P-sorption for each layer). *Surface residue* (crop and manure type and quantities, C, N and P) and *Management practices* (dates of all operations, sowing depth, plant density, type and amount of fertilizer, tillage which include type, depth, fraction of above ground materials incorporated), (*McCown, et al,. 1996*). The complexity and uncertainty of the direct effects of temperatures, rainfall and CO_2 to agricultural crop remains a research question that needs answers. There are different sources of uncertainties encompassing yield estimate by APSIM crop model. The main source of uncertainty at the site level relates to the use of crop models used to derive the yield functions since it makes a number of simplifications (*Parry et al., 2004*). For example, weeds, diseases, and insect pests are assumed to be controlled; and there are no problems with soil conditions (e.g., salinity or acidity).

2.8 Climate Change Scenarios

A scenario is a coherent, internally consistent and plausible description of a possible future state of the world *(IPCC, 1994).* It is an alternative image of how the future can unfold and not a forecast. A *projection* may serve as the raw material for a scenario, but scenarios often require additional information (e.g., about *baseline* conditions). A set of scenarios is often adopted to reflect the range of uncertainty in projections, *(IPCC, 2007).*

Climate scenarios are plausible representations of the future with our understanding of the effect of increased atmospheric concentrations of green house gases (GHG) on global climate. Unlike weather forecasts, climate scenarios are not predictions. They are consistent with assumptions about future emissions of GHG and other pollutants. A range of scenarios can be used to identify the sensitivity of an exposure unit to climate change. This in turn helps policy makers decide on appropriate policy responses to the change, *(Lu, 2006).*

In 2000, the IPCC published a set of emissions scenarios for use in climate change studies (Special Report on Emissions Scenarios – SRES). The SRES scenarios were aimed at exploring future developments in the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions. Four narrative storylines were defined by SRES and named A1, A2, B1 and B2. These scenarios describe the relationships between the forces driving greenhouse gas and aerosol emissions and their evolution during the 21st century for large world regions and globally, Figure.5.

Baseline/Reference The baseline (or reference) is any datum against which change is measured. It might be a current baseline that represents observable, present-day conditions or future baseline, projecting future set of conditions excluding the driving factor of interest. All scenarios were designated as equally valid, with no assigned probabilities of occurrence.

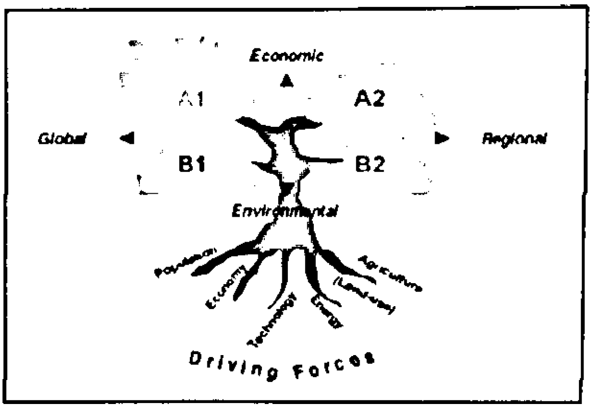


Figure 6: Scenario driving forces.

Six groups of scenarios were drawn from the four families; one group each in the A2, B1 and B2 families, and three groups in the A1 family, characterising alternative developments of energy technologies.

- Scenario A2: The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.
- Scenario A1B: A balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies).

The main finding from the comparison of SRES and scenarios in the literature is that the uncertainties as represented by the ranges of main driving forces and emissions have not changed very much. The range of emissions scenarios reported before and after TAR in scenarios without climate policy seems not to have changed appreciably.

2.9 Global Climate Change Models CSIRO MK 3.6

2.9.1 Climate Model Description

The CSIRO MK3 climate system model was developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia at the CSIRO Australian Numerical Meteorology Research Centre. The Mk3 version of the CSIRO model contains a comprehensive representation of the four major components of the climate system atmosphere, land surface, oceans and sea-ice. The atmospheric model dynamical core has been developed entirely in-house. The same applies to the land-surface (vegetation canopy) model and sea-ice model. The cloud scheme has been coupled to an atmospheric convection scheme in a way that is derived from that used in the Hadley Centre model. The oceanic model is based upon the GFDL Ocean General Circulation Model, the MOM2 code. These components can be used independently, provided that the appropriate boundary forcing fields are provided. Before the Mk3 coupled model was assembled, the separate AGCM and OGCM modules undergo extensive development and testing.

CSIRO-Mk3.6.0. Model is developed by Commonwealth Scientific and Industrial Research Organization (CSIRO) in collaboration with Queensland Climate Change Centre of Excellence It has a resolution of 1.8°x1.8°. The model is assembled from two independent major modules. The AGCM (the Atmospheric General Circulation Model), which contains the atmospheric, land surface, and sea-ice components, and the OGCM (the Ocean General Circulation Model). The ocean component for the Mk3 model is based on the GFDL MOM2.2 ocean model *(Gordon et al., 2010)*. It was configured with the specific aim of forming the coupled model with non-overlapping grid boxes when using T63 atmospheric resolution. However, the ocean model resolution is enhanced (relative to the AGCM) in the meridional direction in order that a more adequate representation of highly important El Niño features is obtained. The meridional resolution of the OGCM has thus been set at double that of the AGCM. The resolution is 1.875°EW x (approx.) 0.9375°NS (sometimes referred to as "T63_2" resolution). This means that, horizontally, there are two ocean grid boxes to each atmospheric grid box in a coupled configuration. There are 31 vertical levels in the ocean model. The Mk3 AGCM is a spectral model developed specifically to use horizontal spectral resolution T63 [1.875°EW x (approx.) 1.875°NS] with 18 vertical levels which is also an AGCM resolution for the coupled Mk3 model (*Gordon et.al, 2010).* The spectral model contains a Semi-Lagrangian Transport (SLT) method for the moisture components and atmospheric tracers such as aerosols. The number of grid boxes in the horizontal for the AGCM (T63) is 192 (EW) x 96 (NS) = 18,432. The vertical coordinate of the AGCM (18 levels) is a hybrid ($p\sigma$) vertical coordinate, where $spp/{=}\sigma$, with being the vertical pressure and the surface pressure. The Mk3.5 model has the same horizontal and vertical resolution as used in Mk3.0, but there have been some significant changes to model physical parameterization and the inclusion of representations of additional physical processes.

a. **Atmospheric parameterizations** The physical parameterizations used in the atmospheric model were modified to some extent for the Mk3.5 model version. Minor changes were made to improved conservation properties or more exact representation of certain processes. Some of the more significant changes are radiation and cloud microphysics. The Mk3 model time-step is 15 minutes while it calculates radiation every

2 hours, *(Gordon et. al., 2010).* The surface long-wave radiation is allowed to vary according to the varying surface temperature on a time step by time step basis. There's an improvement in the computation of absorption by the atmosphere of the surface long-wave radiation between radiation steps. The effect has been to remove an unrealistic concentration of the variation in longwave forcing (due to the changing surface temperature between radiation steps) in the boundary layer, especially for clear skies.

b. **Cloud microphysics** The overall energy balance of the AGCM was altered by the minor changes to the atmospheric and surface physical parameterizations. Annual mean energy balance at top-of-atmosphere was achieved by making some small alterations to the cloud microphysics properties.

The Mk3.5 model has been used in a long control run (1300 years) and for climate change experiments. The Mk3 model is a fully coupled ocean-atmosphere system, without the need for any adjustments of the interactive fluxes and component fields (for example, surface temperature) that couple the atmosphere to the oceans. The initial phase of development resulted in the Mk3.0 coupled model *(Gordon et al. 2002).* Simulations from the Mk3.0 model were contributed to the multi-model set used in the IPCC AR4 assessment *(Randall et al., 2007).* The second phase of development aimed to improve the coupled model climate simulation beyond that of the Mk3.0, by means of improved and/or extended physical parameterizations. This phase, lasting from about 2001 to 2005, resulted in the Mk3.5 model version.

2.9.2 Applicability of CSIRO Model in crop production

Products from CSIRO MK3 have been extensively used in investigation the impact of climate change on crop production around the global. In Thailand, *Sangpenchan, (2009)* conducted climate impact assessment to evaluate potential cassava root crop production in marginal areas of Northeast Thailand using climate change projected by the CSIRO-Mk3 model for 2009–2038. His results showed that an increase of 1-2°C of temperature reduced cassava yield by 28%. In another study, *Mpelasoka et al., (2009)* investigate spatial and temporal characteristics of drought duration, frequency and severity over Australia using Palmer Drought Severity Index (PDSI) from 1951 to 2004 by applying the PDSI to the 20th century Special Report for Emissions (SRES) A2 experiments of CSIRO Mk3.5 GCM for the period 2051 to 2100. The results showed that the CSIRO Mk3 GCM generally captures most of the characteristics of the observed drought events, except for relatively low spatial correlations. This was attributed to spatial scale resolution mismatch between the model and observations.

CHAPTER THREE

3.0 Data and Methods

This chapter describes in detail the type of data used and their sources, as well as the methodology used to achieve the objectives of this study.

3.1 Data Requirement

The study utilised various data sets in order to meet the above objectives. A set of data required for modelling yields response to climate variability is composed of climate data (rainfall, maximum and minimum temperatures, radiation data). Reliability of any crop model also depends on accuracy of the data input. Such kind of data needs to be continuous and homogeneous. Likewise soil influences crop water use through infiltrations rate and the resulting yield output, as such soil characteristics need to be known. Crop production in the study area is supported by soils studies conducted on several locations to determine the soil type, water content, fertility and textures. The samples were found to have semi-arid brown vertisols soils (known as Makande) (*Chilimba et al., 2011*). These soils are comprised of fine-textured clay loam, (*Saka, et al,. 2003*). In some areas, a 2010 sampling show availability of Eutric Vertisol with pH values ranging from 6.97–8.02 in sites like Mangoti (-16° 45'; 35° 15'), Dolo (-16° 33'; 34° 55') and Mikalango (-16° 25'; 34° 49') , (*Chilimba et al, 2011*). The relationship of climatic factor, soil, management, and cultivar contributes to optimization of the final yields where influence of future climate change is negatively thought to alter the relationships.

3.2 Data Type and Source

The data used in the present study included both the observed and simulated data. The observed data consisted of daily maximum and minimum (1971-2002) covering temperatures, solar radiation from Makhanga and Ngabu; daily rainfall (1960-2011) from Nchalo, Ngabu, Makhanga and Chikwawa. Daily projected Global climate model (GCM) outputs data was obtained from the European Climate Assessment Data and KNMI Climate Explorer (KNMI*)* for ensemble mean of CSIRO MK 3.6 a Coupled Model Inter-comparison Project phase 5 (CMIP5) multi-model dataset (*Mitchell et al. 1989; http//climexp.knmi.nl/get_index.cgi)*. The daily maximum and minimum temperatures, daily rainfall and radiation data records were from 1961-2000, and future climate variable were from 2046 to 2100. Even though the period 1961-1990 is often used as the baseline for climate change impact analysis, in this study the period adopted as the baseline was a 30-year climate 'baseline' 1971-2000, following the convention of *Hennessy, (2007)*. The period reflects the recent climate better and was used to capture inherent climate variability at each site. The observed climate data set was obtained from the Department of Climate Change and Meteorological Services (DCCMS) in Malawi; Shire Valley Agriculture Development Division (SVADD) provided sorghum yield data sets comprised of two cultivars, Pirira (*early maturity*) and Thengulamanga (*late maturity*) for the period 1984 to 2010.

3.3 Methods and Techniques

Appropriate statistical test were selected through careful consideration of the data available and the limitations of the tests. This section discuss in details the methods carried out in analyzing data sets. A brief discussion of data relationship from within and between stations was also presented through time series plots, correlations and multiple regressions. A detailed explanation of steps that were carried out in order to develop models that explains the relationship of variables and yields was presented.

3.3.1 Data Quality Control and Analysis.

Quality control of the data was performed by manually checking the missing data, extreme values and incorrect values. The consistency of rainfall data, temperatures and sorghum yield data was tested using single mass curve method while the missing data were estimated using the arithmetic mean method. The data was arranged in a format applicable to the statistical packages used, in this case, Excel, R Gui and APSIM crop model. The effect of past climate on sorghum production was analysed at four stations in Shire Valley area on seasonal and annual means of 3 climatic variables (rainfall data (1961–2010); temperatures and radiation (1971-2004)). The variables included daily mean (T), maximum (T_{max}), and minimum (T_{min}) temperature and rainfall amount (PR). The daily mean temperature was defined as average of today maximum temperatures and minimum temperature of the following day $[T_{max,i}+T_{min,i+1})/2]$. To assess the likely impacts of global climate change on sorghum yield production, the study compared rainfall and temperature from Shire Valley with GCM scenarios for 1971 to 2000. Climate scenarios evaluated was based on daily rainfall, daily radiation and temperature (minimum and maximum) extracted from grid cell (15.4-17.8°S) and (33.8-35.5°E) covering Chikwawa, Makhanga, Nchalo, Ngabu, and Nsanje which are located at 35° 10' E, 16° 30' S; 35° 16' E, 14° 29' S and 34° 35' E, 13° 45'S respectively. *Lines, et al., (2005)* detailed a description of the method used to downscale projected climate change parameters which is not be included in this paper. As done with the observed data, CSIRO MK3.6 model outputs (seasonal mean rainfall and temperatures) for present (1971-2000) were used in the APSIM model to serve as baseline scenarios after a correction factors was applied. The effect of the current climate variability was determined on the model results and the observed sorghum yields.

Data reliability was checked by applying homogeneity test which involved comparison of data from one station to its surrounding stations. Single mass curve and moving average plots was used in this research to test for homogeneity. The linearity of the plots indicated homogeneity of the data, otherwise heterogeneity was be depicted by non-linear plots.

3.3.2 Estimation of Missing Data

There are several methods of estimating missing climatic data record. Type of method depends on whether the missing data are temporal or spatial data. Temporal resolution is good for annual, monthly, daily and hourly, etc. depends on the length or amount of missing records. In some cases, certain methods (e.g. methods based on time series analysis) can only be applied depending on the available record length (*Salas,et al, 2006*). Apart from normal ratio, inverse distance method, correlation and regression, this research employed arithmetic mean method which is the simplest and by far the most used method in estimating missing data. It involves replacing the missing data with the average or the mean for a given station and it is given by the following relationship;

$$Xm = \left(\frac{\bar{x}}{\bar{y}_a}\right)y_a \qquad (1)$$

Xm is the missing data, $\bar{x}$ is the mean of x observations of the station with the missing data, $\bar{y}_a$ is the mean of y observations with data and y_a is the available value of the nearest station with highest correlation with the station with missing data.

3.3.3 Time Series Analysis.

The components of any time series consist cycle variation, trend and random variation depict characteristic variations. Analyses of such variations constitute time series analysis. A time series by definition is a collection of observed data at equal intervals of specified time. From a statistical point of view, the study of climatic variability is a problem of time series analysis (*Raziei,et al., 2005*). Statistical evidence of persistence in such time series is equated with evidence of unquestionable climatic fluctuations and said to be dependent. A time series is not statistically independent in many cases, but is comprised of persistence, cycles, trends or other random components. When the nature of the trend is subject to change over short intervals of time it is termed local trend, or, on the other hand, it can be visualized as global trend that is long lasting (*Rai, et al., 2010*).

3.3.3.1 Determining Spatial and Temporal Variability of Rainfall and Temperature

Climate variability refers to the deviation of climate statistics over a given period of time (for example a specific month, season or year) from the long-term climate statistics relating to that corresponding calendar period. Coefficient of Variation (COV), a critical variable for assessing variability in rainfall was applied to monthly meteorological data. Change in the mean total rainfall accompanied by other changes like the rainfall frequency or distribution to check for variability were also analysed. All these changes were noted to have effects on various aspects of rainfall extremes including the intensity of rainfall (*Pancura and Lines, 2005).* Significance of individual events such as the El Niño or El Niña Southern Oscillation phenomena on climate variation was also assessed.

Observed data sets and downscaled data sets were used to analyse variability and extremes of the data sets. Regular or nearly regular observations were used to study seasonal variation. Rainfall variability was determined by was calculation of Coefficient of Variations of rainfall (COV%). Coefficient of Variation (COV) is a statistical measure of how the individual data points vary about the mean value, *(Trenberth, 1984).* COV is calculated by dividing the mean into standard deviation to allow comparisons of rainfall variability (*WMO 2006*). Values less than or near 1.00 indicate that the data form a relatively close group about the mean value. Values larger than 1.00 indicate that the data show a greater degree of scatter about the mean.

Coefficient of Variation (COV) = Standard Deviation/Mean. *(5)*

The mean data subsets were subjected to both *F-test* and *T-test.* Details of these tests can be found online as well as in most statistical books. According to (*IPCC, 2001*), temperature is considered to be normally distributed and for this study variability in its distributions was analyzed using probability distributions and histograms. Differences in the means and the variance (standard deviation) between historical and projected distributions were analyzed for variability i.e. for changes in probability of occurrence of particular extreme events. Extreme events were also analysed using derivative series. Derivative series is a very useful method to check on the rate of change of magnitude at the consecutive time instants, (*HP, 1999*). The extreme negative (positive) values indicate a very wet (dry) year. Derivatives series Z_t is given by $Z_t = x_i - x_{i-1}$. Where x is an observation at initial time i and i-1.

Finally, RClimDex (1.0) software developed and maintained by Xuebin Zhang and Feng Yang at the Climate Research Branch of the Meteorological Service of Canada *(Zhang and Yang, 2004)* was used in the extreme indices analysis. RClimDex, a R based package (R is a language and environment for statistical computing and graphics which is a GNU implementation of the S language), is designed to provide a user friendly interface to compute indices of climate extremes as recommended by the CCI/CLIVAR Expert Team for Climate Change Detection Monitoring and Indices (ETCCDMI). It also computes the linear trends of the indices and gives an assessment of statistical significance, for each individual weather station. In this work, the occurrence of the extreme events in terms of maximum and minimum temperatures (Tx, Tn respectively), their duration and intensity, and their trend over the last decades for each station were analyzed.

3.3.3.2 Persistence

For change in the climatic variable, persistence is parameter that can be used to determine the presence of trend in a time series. In its definition, persistence as given by *WMO (2000)* with value of lag1 (r_1) has been used to detect the possible persistence in the observed year-to-year variations of normalized anomaly series and to examine its nature and magnitude. The approach was proposed by *WMO* and *Matalas, (1967)*. The normalized anomaly (X_t) for this work was calculated as follows

$$X_t = \frac{x_t - \bar{x}}{\sigma} \qquad (2)$$

Where x_t is the normalized anomaly of the series, x is the observed time series, $\bar{x}$ and σ are the long-term mean and standard deviation of annual/seasonal time series.

Serial correlation coefficients (SCC) of normalized climatic series was computed for lags $L = 0$ to m, where m is the maximum lag (i.e. $m = n/3$); n is the length of the series. The serial correlation coefficient was computed as;

$$r_L = \frac{\sum_{i=1}^{n}(X_t - \bar{X}_t)(X_{t+L} - \bar{X}_{t+L})}{\sqrt{(\sum_{i=1}^{n}(X_t - \bar{X}_t)^2 \sum_{i=1}^{n}(X_t - \bar{X}_{t+L})^2)}} \qquad (3)$$

where r_L is the lag-L serial correlation coefficient of the series. The significance test of serial correlation is found using eq. (4).

$$(r_L)_{t_g} = \frac{-1 \mp (n-L-1)^{1/2}}{n-L} \qquad (4)$$

Where, $(r_L)_{t_g}$ is the normally distributed value of r_L, t_g is the normally distributed statistic at g level of significance. The value of t_g are 1.645, 1.965 and 2.326 at significance level of 0.10, 0.05 and 0.01, respectively. The hypothesis tests were carried out at a significance level of 0.05. Statistically 95% data explanation by any model or analysis gives sufficient results for use in agriculture. The 'null' hypothesis of the randomness of climatic series against the serial correlation was rejected for the large value of r_1. If r_1 of the series was not statistically significant or was significant but had a negative sign, it was assumed that the series did not contain the persistence and the appropriate null continuum was termed as 'white noise'. On the other hand, the persistence in the time series was characterized by a positive serial correlation. In this case, a "Markov red noise" type 'null' continuum was ensured using r_1 and r_3, (*WMO, 1966*). In addition to this significant negative r_1 was an indicative of high-frequency oscillations, whereas significant positive r_1 was indication of low-frequency fluctuations and persistence in climatic series.

3.3.3.3 Trend Analysis

Trend analysis was performed using non parametric approach. This approach, Mann-Kendall (MK) test is the most popular approach in detecting trend for different climatic variables time series (*Gilbert, 1987*; *Hirsch, et al., 1982*). When observations are divided into separate classes according to the season and Mann-Kendall trend test performed on the sum of the statistics, effects of seasonality are eliminated. Both approaches were used in this work. The Mann-Kendall test for detecting monotonic trends in climatic time series is described by *Yue et al. (2002)*. It is based on the test statistics S, which is defined as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \qquad (6)$$

Where, *xj* are the sequential data values, *n* is the length of the data set and

$$sgn(t) = \begin{cases} 1. & for\ t > 0 \\ 0. & for\ t = 0 \\ -1. & for\ t < 0 \end{cases} \qquad (7)$$

The value of S indicates the direction of trend. A negative value indicates falling while positive is a rising trend. Mann-Kendall documented that when $n \geq 8$, the test statistics S is approximately normally distributed with mean and variance as follows

$$E(S) = 0 \qquad (8)$$

And variance of *S* (eqn.9) where *n* is the length of the time series, *m* is the number of so-called *ties* (ties means values that have duplicates) and t_i is the numbers of duplicates for tie *i*.

$$Var(S) = \frac{1}{18}[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)] \qquad (9)$$

Then for fairly large n, $\frac{S}{\sqrt{Var(S)}}$ is approx. $N(0,1)$ if H_0 is true.

Where, m is the number of tied groups and t_i is the size of the ith tie group. The test result (standardized test statistics Z) is computed as follows.

$$Z_{mk} = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & for\, S > 0 \\ 0 & for\, S = 0 \\ \frac{S+1.}{\sqrt{Var(S)}} & for\, S < 0 \end{cases} \quad (10)$$

The standardized Mann-Kendall statistics Z follows the standard normal distribution with zero mean and unit variance. The null hypothesis H_0 is accepted if $-Z_{1-(\alpha/2)}. \leq Z \leq Z_{1-(\alpha/2)}$. For this study, the significant level of 0.05 was applied, and observes p-values obtained for each analyzed time series. The null hypothesis about no trend was rejected at the significance level α (5%).

3.3.3.4 Cox-Stuart Test

The Cox-Stuart test is defined as a little powerful test (power equal to 0.78), but very robust for the trend analysis (*Cox and Stuart 1955*). The proposed method is based on the binomial distribution and is applicable to a wide variety of situations, *(Tommaso, 2009)*. This method was used to verify significance of trend and establish magnitudes of variability and direction of change. The method is more useful for detecting magnitude and direction when Mann Kendall test is used.

3.3.4 Effects of present and future Climate Change on Sorghum Yield

In order to determine the effects of climate on sorghum yield, and to draw from temporal attributes of climate dataset and cross-sectional, a multiple regression model was used. The model is given as

$$\boldsymbol{Y_i = a + \sum_{j=1}^{m} b_i X_{ij} + e_i} \qquad \textit{(11)}$$

where a is an intercept, *b* is coefficient for variable *X*, the subscript *i* refers to the *ith* observation and the subscript *j* refers to the *jth* predictor and *ei* is the difference between the *ith* observation and the model; *ei* is the error term. Assumptions are that the relationship between X and Y is linear, the expected value of the error term is zero, the variance of the error term is constant for all the values of the independent variable, X. There is no autocorrelation, **E(*ei ej*) =0**. The independent variable is uncorrelated with the error term and the error term is normally distributed.

3.3.5 Sensitivity analysis of climatic variable on Sorghum Yield

Sensitivity analysis was performed to estimate the relative participation of climate variables to the calculated yields. There are several approaches available for sensitivity analysis studies, as reported by *Bois et al. (2008)*. This study used Pearson correlation coefficients "r" on a seasonal basis for maximum, minimum mean temperatures and rainfall.

3.4 Simulations of the impact of climate change on Sorghum yield

To determine the effect of climate change on sorghum yield, present and future climate elements were related and output compared to the observed sorghum yield.

3.4.1 APSIM Model Parameterisation and Management practices

Two variety of Sorghum cultivar (Thengalamanga hereafter SVLocal) an early maturity cultivar with 110-120 days, 71 days to flowering and Pirira 2 (ICSV 112 hereafter SVHybrid) a late maturity cultivar with 120-149 days and 69 days to flowering were used to calibrate the model for the study region. The model soil parameters and genetic coefficients for Shire valley growing conditions and cultivar were parameterized for brown vertisol (Makande) Ngabu SV9801 soil conditions. Soil nitrogen, soil water, and residues were considered with start of the season set on the 15th November for each year simulation run. The spatial distribution of yield as a factor of soil parameters was not modelled because the adopted soil parameters were assumed to be uniform hence have same effects on yield.

The APSIM model was used to simulate long term effects of climate variability on sorghum grain yield using the following sowing rules if cumulative rainfall within 2 days >= 20 mm between 15 of November and 10 of January, then sow both variety. Sowing density was 8 plants/m^2, planting depth of 30mm, 0 and 25kg/ha, 50kg/ha Urea-N and NO_3-N was applied during sowing at a depth of 5 cm with Phosphorus at 5-7kg/ha. In addition to nitrogen fertilizer, initial soil nitrate-N was set at 12 kg NO_3/ha in the top 35cm of the soil profile for Shire Valley. These levels were chosen to represent a non-limiting nitrogen environment and considered the most economical fertilizer application practices. The crop model incorporated CO_2 fertilization to assess climate-change effects on sorghum. In order to explore the direct effects of CO_2 on grain yield, CO_2 levels were set to 350ppm (baseline) and 2xCO_2 respectively. However, the primary assumption was that, plants with similar photosynthetic metabolic pathways would react similarly to any given climate-change effect in a particular geographic region.

Low input subsistence farming characterise the areas; fertilizer application is not done in the area. At the end of each season, crop residues are removed for domestic use (e.g. fuel, fencing and animal feeds). Therefore, to optimise production, assessed of the following management scenarios was done; (a) No mineral fertilizer inputs for current climate scenarios, (b) Application of mineral fertilizer for current climate scenarios, c) Application for future climate scenarios using strategy (a) and (b).

3.5 Evaluation of Model skills

3.5.1 Root Mean Square Error (RMSE) and Index of Agreement

The performance of APSIM Sorghum and Linear Mixed Models was statistically evaluated using root mean square error (RMSE) and Bias, The index of agreement (d) in equations 12 and 13 was used to assess the predictive power of the regression equations and APSIM models (*Willmott et al 1985; Loague and Green, 1991*). Observed and projected yield data for 1984-2010 was used as indicators for establishing the accuracy of climate variability impacts on yield outputs.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_{model,i} - X_{obs,i})^2} \qquad (12)$$

3.5.2 Index of agreement d

The index of agreement (d) was proposed by *Willmot (1981)* to overcome the insensitivity of Nash-Sutcliffe model efficiency coefficient and r^2 to differences in the observed and predicted means and variances *(Legates and McCabe, 1999)*. The index of agreement can detect additive and proportional differences in the observed and simulated means and variances; however, it is overly sensitive to extreme values due to the squared differences [*ibid.*]. The index of agreement represents the ratio of the mean square error and the potential error *(Willmot, 1984)* and is defined as

$$d = 1 - \left(\frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model})^2}{\sum_{i=1}^{n}(|X_{model} - \bar{X}_{obs}| - |X_{obs,i} - \bar{X}_{obs}|)^2}\right) \qquad (13)$$

where $X_{obs,i}$ and X_{model} are the observed and the model simulated yields respectively, n the number of observations, $\bar{X}_{obs}$ is the mean of the observed yield. For a good projection, RMSE and d must b as close as possible to 0 and 1 respectively. High values of d close to 1 indicate good model performance and better relation of observed verses projected.

CHAPTER FOUR

4.0 Results and Discussions

The main objective of this research was to quantitatively gain understanding of the effect of climate variability and change on sorghum yield in the Shire Valley. APSIM Model and regression analysis were used to study the effects of change in temperature, rainfall and solar radiation on sorghum production.

4.1 Data quality control

Temperatures data for Ngabu and Makhanga meteorological station was available from 1971-2004 while data for rainfall for Nchalo Chikwawa, Makhanga and Ngabu was available for 52years starting from 1960. Two stations had few missing data mainly in the temperatures records; Makhanga and Chikwawa had rainfall missing data less than 10%, 1990 for Makhanga and 2005 for Chikwawa. All the data was then checked for consistency. Arithmetic mean method was used to fill in the missing values. One station (Nsanje) had missing data more than 10% of its available data and hence ignored. On the other hand, climatic time series often exhibit spurious (non-climatic) jumps and/or gradual shifts due to changes in station location, environment (exposure), instrumentation or observing practices. There homogeneity tests of these climate helps to detect and correct these changes.

4.1.1 Consistency of the Data

Both temperatures and rainfall data were examined for consistency. A test of homogeneity using a single mass curve method was performed on rainfall, yield, maximum and minimum temperatures. Linear graphs in Figure.7 (a-d) depicting homogeneity which led to acceptance of the data for further analysis. However, the mass curve for sorghum yield showed that heterogeneity in the year 1990/1991 and this discrepancy was caused by drought that affected the areas. For heterogeneity cases, the correction on rainfall was done by plotting a straight line joining points of homogeneous raw data and extending the line to the heterogeneous data in a mass curve. A correction factor was given by the ratio of the gradient of the homogeneous data line to the gradient of the heterogeneous multiplied to the homogeneous data.

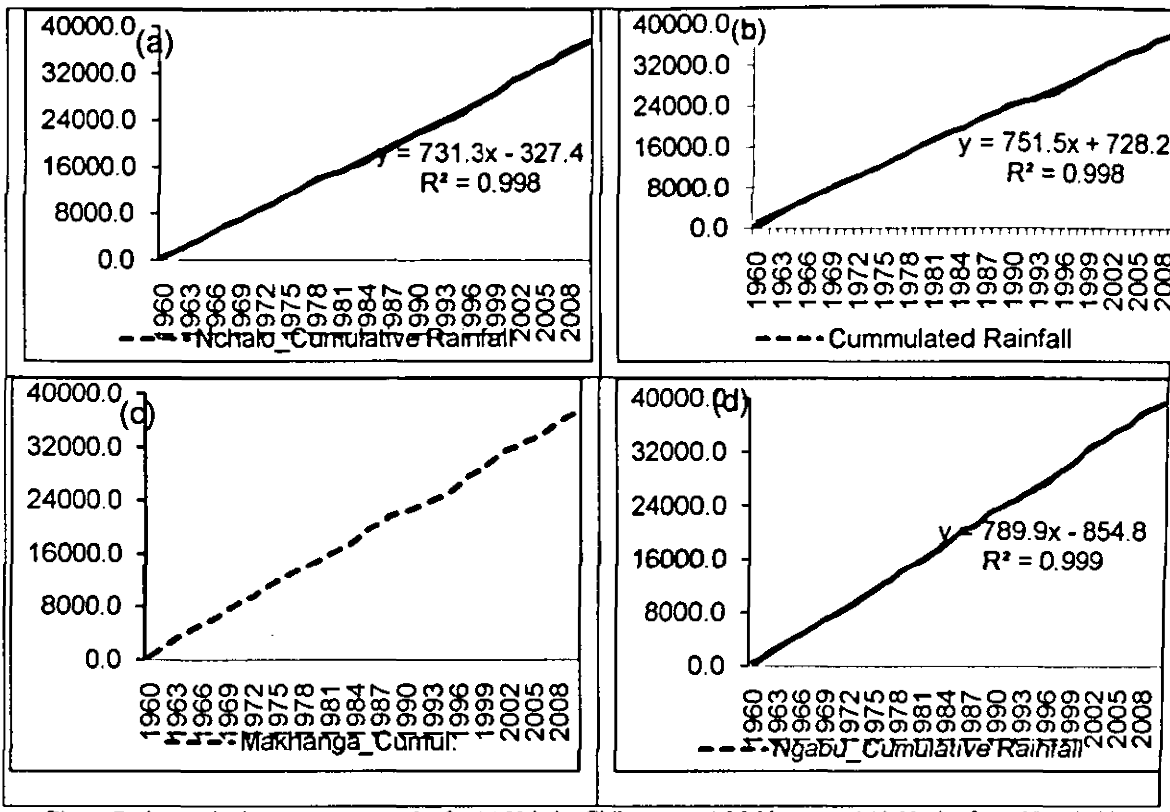


Figure 7: shows single mass curve graphs for (a) Nchalo, Chikwawa, (c) Makhanga and (d) Ngabu from 1960-2011

4.1.2 Test for Normality in the Climate Variable

Seasonal rainfall for the study sites was analyzed for normal distribution. The results are shown in Figure.8, 10 and 11. The histogram presented in Figure.9, 10 and 11 does approximate a normal or Gaussian distribution of rainfall and temperatures, as expected for a z-score. The results of the analysis showed normal distributions of rainfall in all the station. Further than that distribution of temperatures also revealed normal distribution of its data.

Further analysis to find the relationship of rainfall distribution to ENSO episodes was done (Figure.8). It was found that different ENSO episodes have different effects on rainfall distribution. During El Niño, the results showed tendency of rainfall to be below average while distribution of neutral conditions showed above average rainfall. During La Nina, generally average rainfall is experienced in the area (Figure.8c). The ENSO episodes also demonstrated the significant of impact on the agricultural activities of the areas.

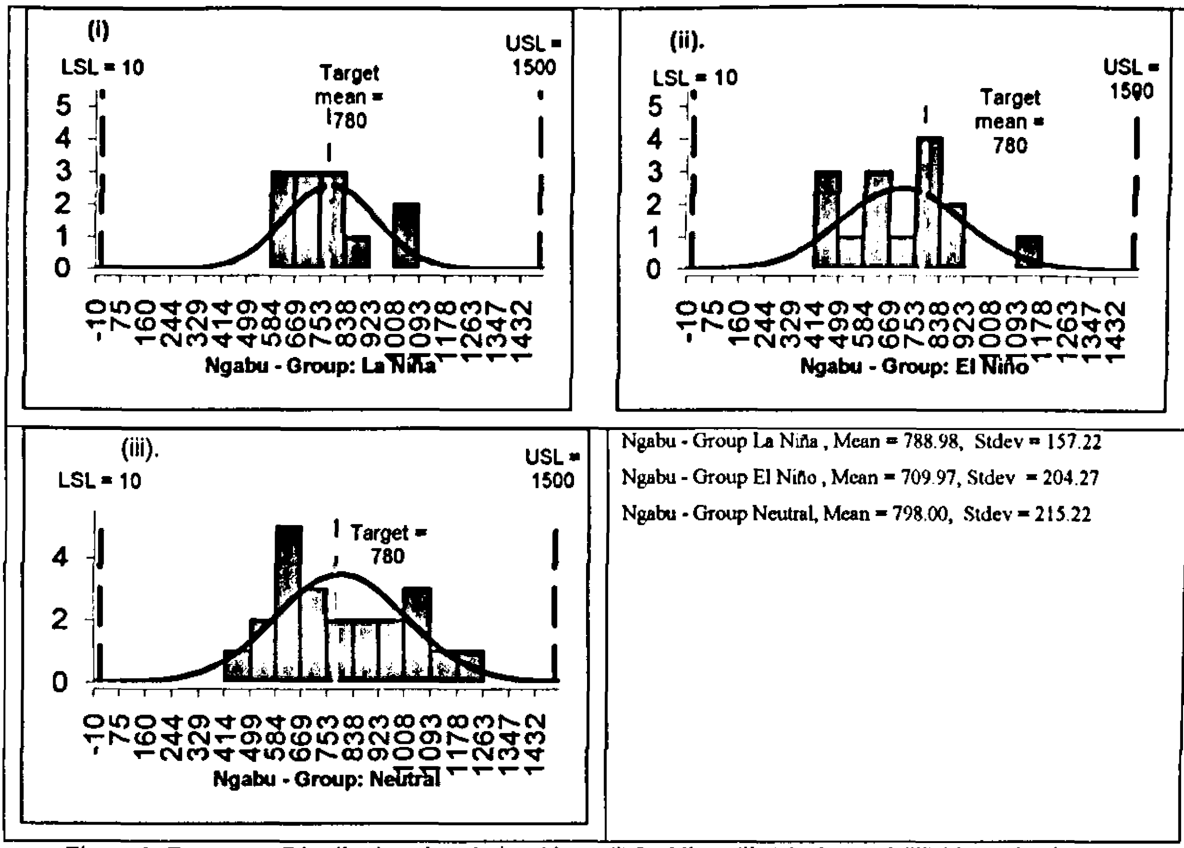


Figure 8: Frequency Distributions in relationship to (i) La Nina, (ii) El Niño and (iii) Neutral episodes.

4.2.3 Rainfall and Temperatures Frequency Distribution

Frequency distribution of monthly rainfall in all the study sites showed increasing incidence of monthly rainfall distribution of threshold below 25mm as noted in Figure.9. All the stations *depicted a similar pattern of distribution as evidenced by Figure.9 although differences in the* frequency of distribution are evident. It was also shown that Nchalo and Makhanga receive more rains exceeding 100mm in a month than Ngabu and Chikwawa. The reason for the extreme rainfall over Makhanga and Nchalo can be linked to the influence of Tropical Cyclone in the Mozambique Channel and warm and moist Congo Air mass. When cyclone is in the channel, Congo air is enhanced over Malawi. This influence benefits Makhanga and Nchalo than Chikwawa and Ngabu due to geographical positions of these sites. The IPCC (2007) also concludes that future tropical cyclones (typhoons and hurricanes) will likely become more intense, with larger peak wind speeds and more heavy rainfall associated with ongoing increases of tropical SSTs. Similarly, distribution of seasonal rainfall in the sites revealed a uniformity pattern of rainfall distribution although there was an increase in total rainfall distribution at Chikwawa as shown by Figure.11.

A quick look on frequency distribution of temperature revealed that there is a high occurrence of temperature for minimum (23°C) and maximum (33°C). However, increase in both the minimum and maximum temperature extreme are observed at Ngabu (min-temp=27°C) and max-temp=40°C as shown in Figure.12. However, Makhanga maximum temperatures showed an increased frequency of temperatures over 40°C as compared to Ngabu. Seasonal rainfall distribution inmdicated concentration of rainfall about 600mm at Chikwawa and Makhanga during JFM while over 400mm was observed at Ngabu. On the other hand, OND showed concentration of rainfall of about 300mm in all the station. However, Chikwawa and Makhanga showed more extreme within a season as observed at Makhanga where rainfall of a 100mm was observed. Increase in magnitude of frequency of OND rainfall distribution for very wet conditions were high at Makhanga while for JFM rainfall, it was high at Chikwawa as as observed by Figure. 11. Analysis of seasonal rainfall in all the stations showed variability in its distribution.

Further scrutiny for temporal consistency in the annual rainfall pattern was done using derivative series. The derivative analysis results (Figure.12 & 13) revealed that Ngabu and Makhanga experienced more extreme events (both dry and wet events) than Chikwawa and Nchalo. It was also shown that extreme rainfall events have increased since 1985. The reason for the increase in the extremes over Ngabu and Makhanga is attributed to the station proximity to the cyclone path (Mozambique Channel) as Nchalo and Chikwawa lie in the rain shadow of Shire highlands. There seems to be alternative negatives and positives in the derivatives series for the area study sites which implied that wet years were following consecutive dry years. An extreme dry year also follows an extreme wet year as shown in Figure.12 & 13 where a dry year 2007 followed a wet year 2008.

Examination of seasonal temperatures for variance in the mean was also done using box plots given in Figure.66 in the appendix. Spatial variability is the distribution of temperatures was observed particularly in minimum temperatures. Minor differences were noted in the mean maximum temperature. Similarly, analysis of temperature variability revealed that temperatures for Ngabu are warmer than Makhanga. During JFM, maximum of Ngabu exceed that of Makhanga with extreme outliers while Makhanga had cooler temperatures, similarly, during AM, JJA and OND, Ngabu maximum temperatures showed they are warmer than Makhanga. Cooler temperatures were observed over Makhanga during the whole year and JJA was shown to be the coolest period where Makhanga JJA was as low as 13°C. The low temperatures over Makhanga for both maximum and minimum temperatures are attributed to closeness of Makhanga to the source of cool Chiperoni winds during winter.

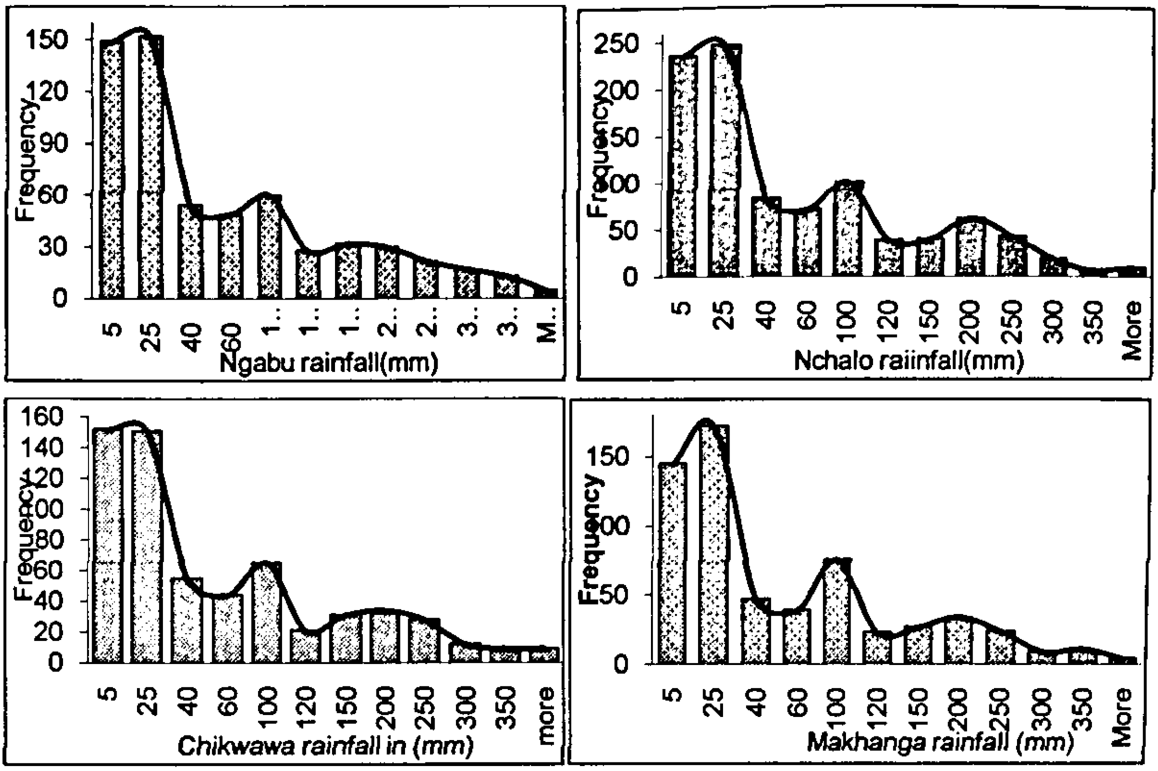


Figure 9: Frequency distribution of monthly rainfall for Ngabu, Nchalo Chikwawa and Makhanga (1960-2011)

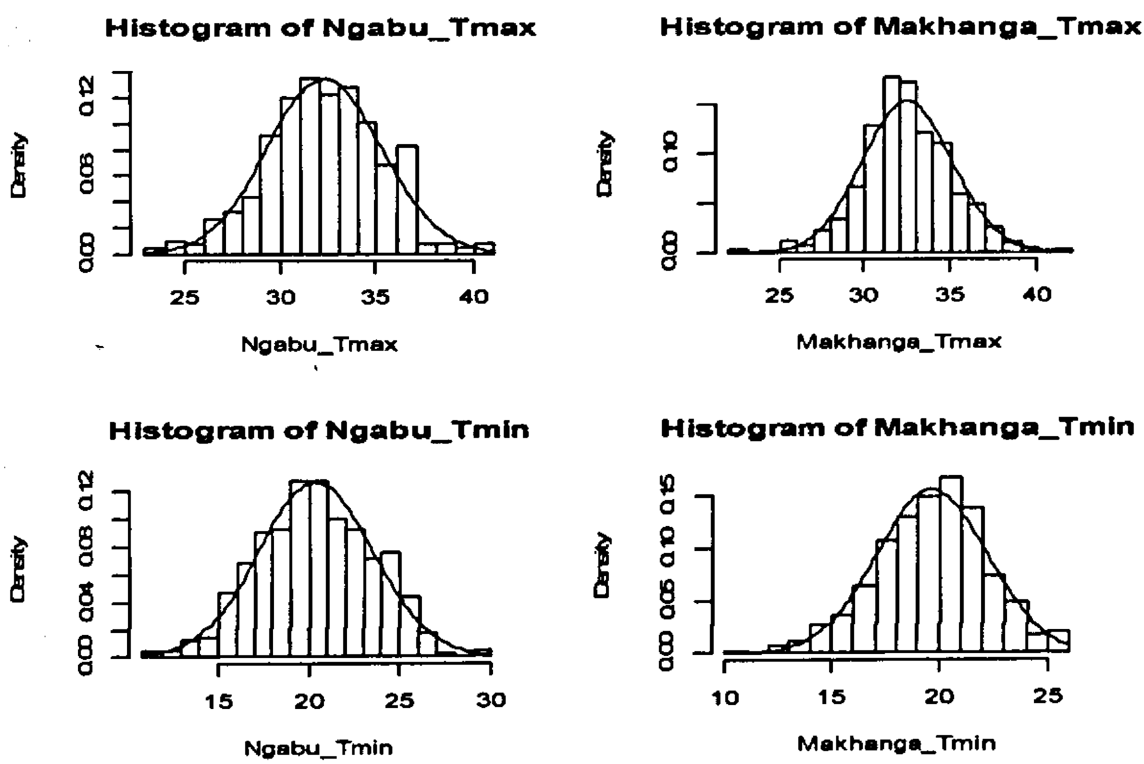


Figure 10: Monthly temperature frequency distribution in the Shire Valley, (1971-2004)

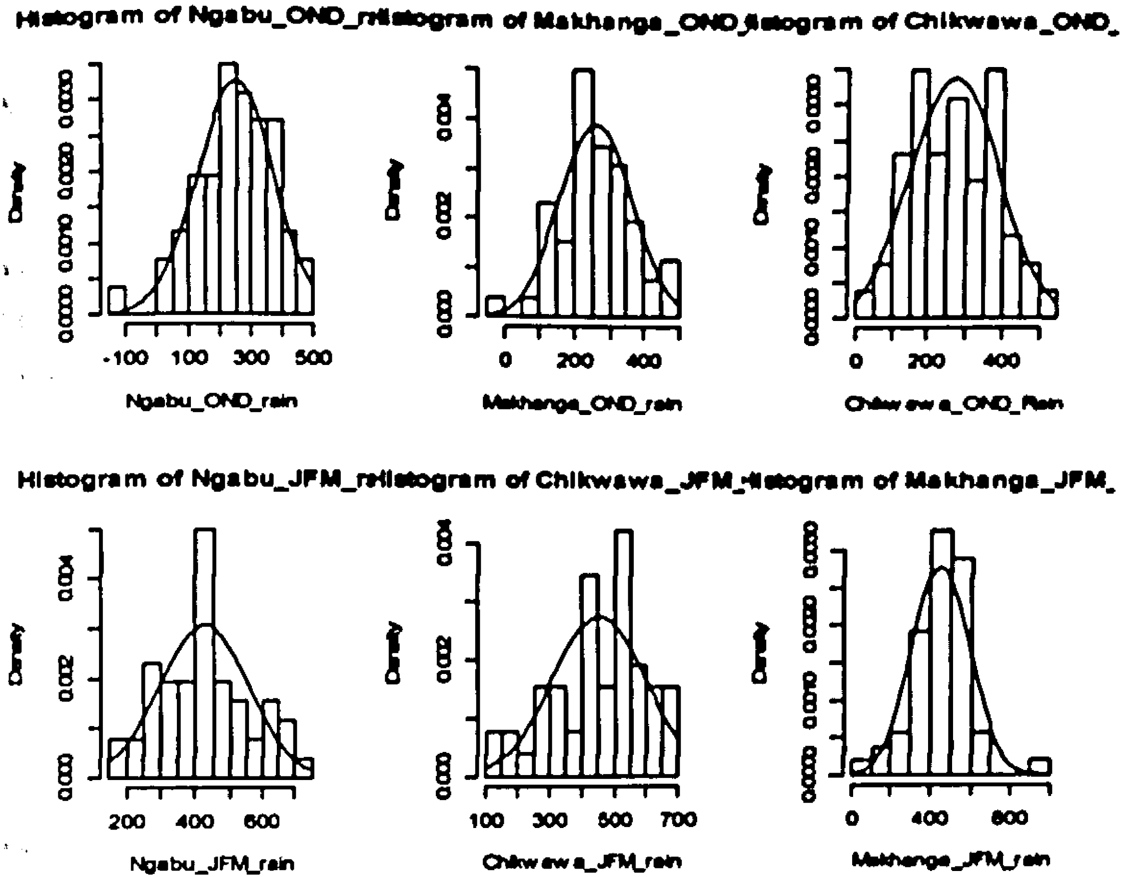
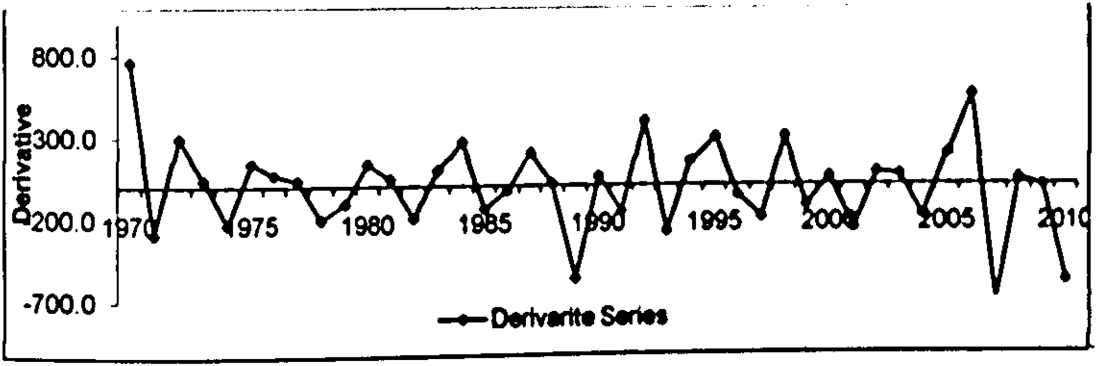

Histogram of Ngabu_OND_rHistogram of Makhanga_OND_Histogram of Chikwawa_OND_
Density
-100
100
300
500
Ngabu_OND_rain
0
200
400
Makhanga_OND_rain
Chikwawa_OND_Rain
Histogram of Ngabu_JFM_rHistogram of Chikwawa_JFM_Histogram of Makhanga_JFM_
200
400
600
Ngabu_JFM_rain
100
300
500
700
Chikwawa_JFM_rain
0
400
800
Makhanga_JFM_rain

Figure 11: Seasonal Rainfall frequency distribution for Shire Valley



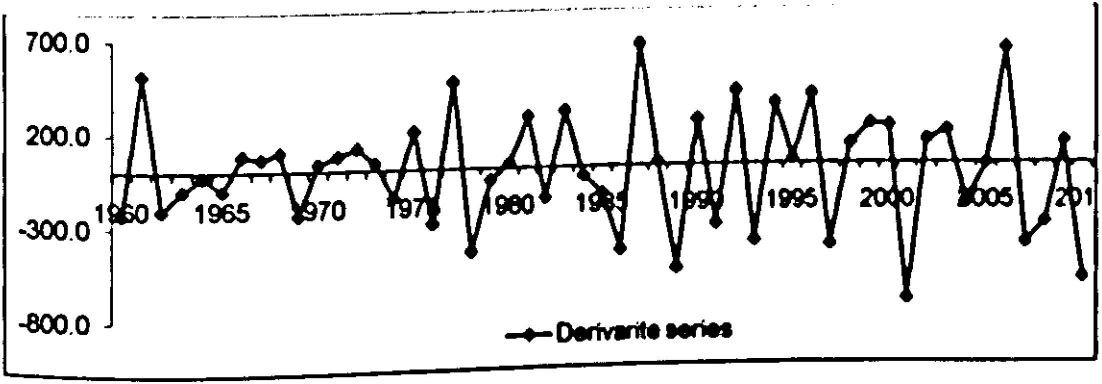


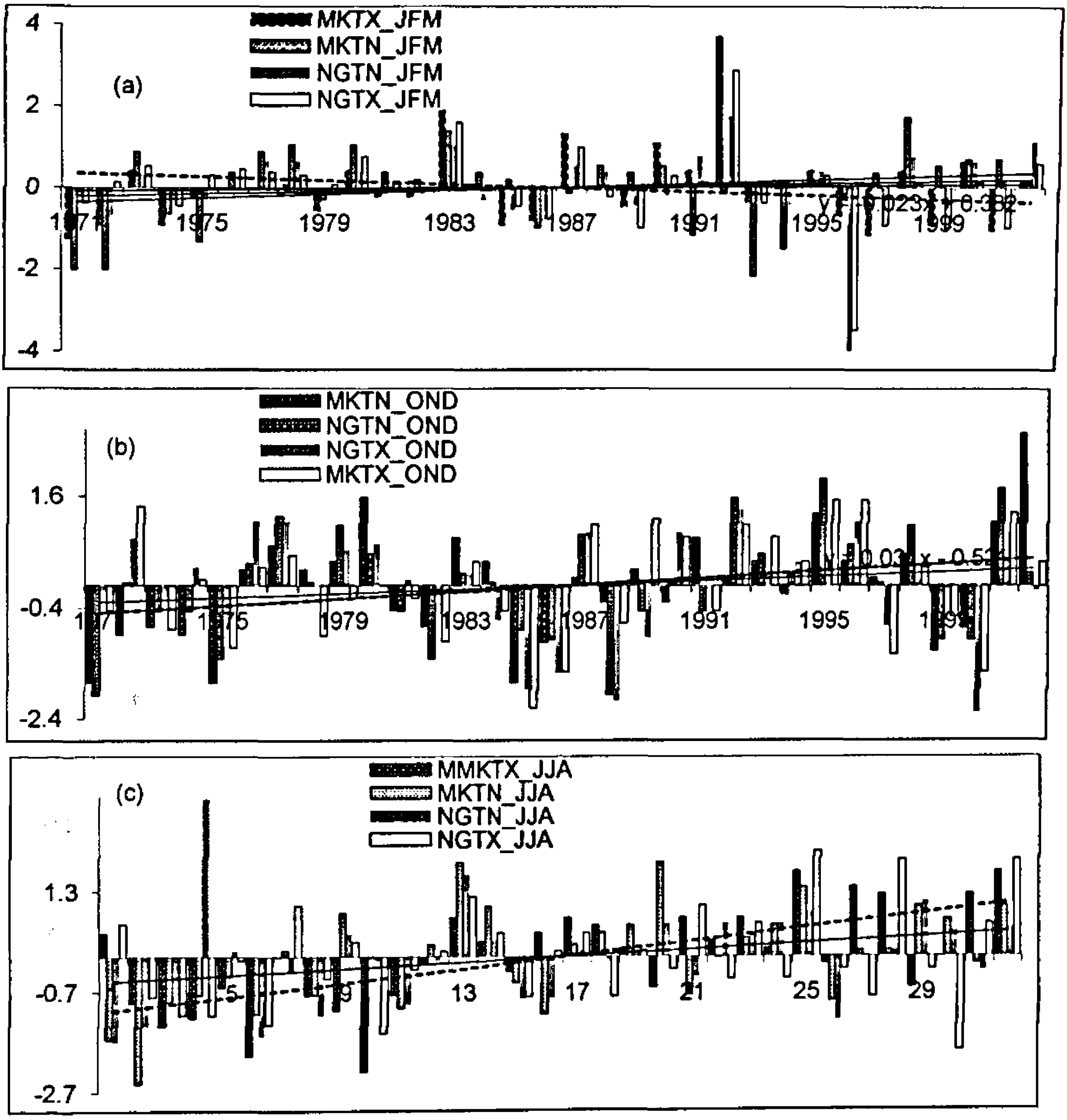
Figure 12 and Figure 13: Derivatives time series for Nchalo and Ngabu in the Shire valley

4.3 Variability and trend of rainfall and temperatures in the Shire Valley

Air temperature trend and summary data for 34-years period over the investigation period for Makhanga and Ngabu stations are shown in Figure 14 and Table 7. The two stations had a *minimum temperature with long-term average mean temperature of* 23.8°C *for* Ngabu and 19.8°C for Makhanga. The mean temperature showed high variation across the year with an annual range of 14.2°C at Ngabu and 23°C at Makhanga (Table 7). Periods of highest maximum temperature was during the onset of rains while periods of lowest minimum temperature was at the end of the season (i.e. October and June) hence high daily temperature range. The difference between maximum and minimum temperature could reach 15.5°C at Ngabu and 22.4°C at Makhanga. Due to the low absolute minimum temperature, crop damage increased through delayed maturity. Cool temperatures implied longer duration to reach crops maturity. This implied that potential for adopting early maturing crop varieties developed for dry hot conditions, which usually have high mean temperatures is limited.

Normalised temperatures for October to December (OND), January to March (JFM), April to May (AM) were further analysed and the results indicated increasing trend in all the time series except for maximum temperatures at Ngabu. The results also showed that increase in minimum and maximum temperatures is more pronounced during JFM and AM which are the critical months for the crop growth in the area. The rates of increase as determined by the gradient are overwhelming. More increase was observed at Makhanga for both maximum and minimum temperatures. Trend of temperatures over Makhanga showed an annual increase of 0.05°C for minimum temperatures as compared to 0.04°C/year at Ngabu. Similarly, maximum temperatures were increasing at 0.03°C annually while Ngabu maximum temperatures were decreasing as shown by Figure.15. This wide variation in the rate of increase observed in the minimum temperatures at Makhanga when compared to uniform increasing rate at Ngabu is a good indication of influence of altitude on temperatures. Likewise, Makhanga is closer to the cool and moist south-easterly airflow during winter period. This also contributes to low temperatures at Makhanga than Ngabu since modification of air temperature may have place by the time the air parcel reaches Ngabu.

From climate variable indicators chosen (Table.2), it was observed that mean rainfall for the whole season was increasing. However, when the season was separated into OND and JFM, the mean rainfall increased than in the whole season (ONDJFM). For all indicators including ENSO episodes, JFM, OND, annual, and seasonal, only seasonal rainfall has a significance that is above the usual cut-off ($p = 0.147$). These results cannot be conclusive since other influencing variables are not controlled for in these outcomes. The distribution can show patterns to indicate how climate variables are affected by variability and how these variables might influence other dependent factors of interest such as crop yield and soil moisture. Makhanga and Ngabu rainfall showed more variability during the month of November and February than the other station. The covariance of coefficients showed increase in variability during 1981-2011 than between 1961-1990



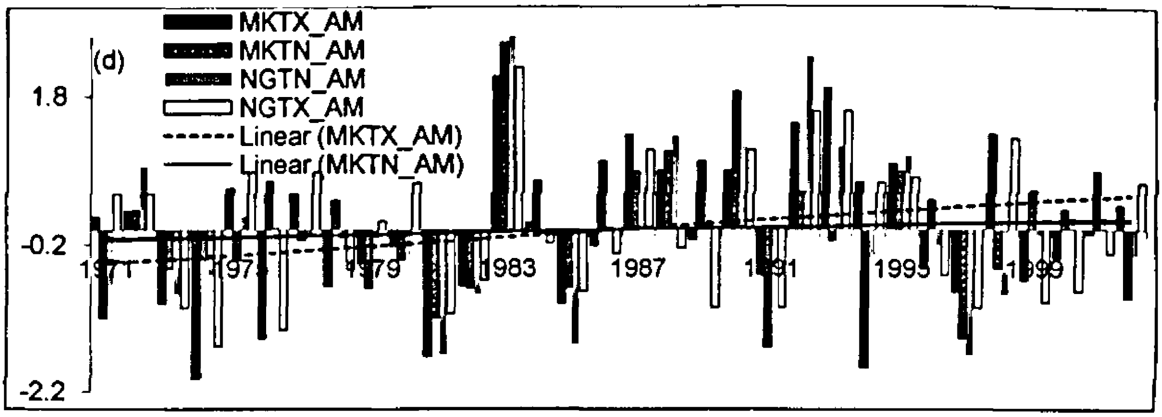


Figure 14: Minimum and maximum temperature anomalies for Makhanga and Ngabu

Table 2 Comparison of spatial variability of rainfall in the Shire Valley (COV(%))

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NCHALO_CV(%)61-90	60.7	60.5	63.1	98.7	135.7	70.0	81.1	139.0	152.9	143.8	68.0	54.5
NGABU_CV(%)61-90	50.9	68.9	68.3	81.9	93.5	89.4	122.7	139.1	183.1	127.4	84.5	53.6
CHIKWAWA_CV(%)61-90	50.9	53.5	86.9	83.4	112.6	88.5	90.2	192.8	166.3	162.1	72.7	65.5
MAKHANGA_CV(%)61-90	51.3	64.1	59.4	71.3	93.2	90.1	87.0	120.7	158.9	119.0	81.9	39.6
NCHALO_CV(%)71-2000	62.6	62.1	65.0	119.0	147.0	95.8	91.0	164.1	160.8	183.5	68.7	63.1
NGABU_CV(%)71-2000	47.5	63.0	70.1	72.0	94.6	81.7	117.4	114.5	145.3	112.4	75.0	57.3
CK_CV(%)71-2000	48.4	59.2	83.8	98.8	106.8	89.8	108.2	160.7	168.2	146.1	67.3	66.0
MAKHANGA_CV(%)71-2000	54.7	84.2	60.3	75.7	87.8	81.0	86.0	135.4	163.1	132.5	71.7	50.2
NCHALO_CV(%)81-2011	63.3	61.6	69.5	76.7	133.3	87.2	78.2	144.9	133.8	157.0	82.2	59.7
NGABU_CV(%)81-2011	53.6	63.1	66.1	77.5	107.1	100.5	121.5	148.0	146.7	116.8	73.1	58.4
CHIKWAWA_CV(%)81-2011	55.8	58.6	88.0	94.9	107.2	138.3	114.0	162.7	208.1	156.3	72.5	73.1
MAKHANGA_CV(%)81-2011	56.8	73.9	64.5	84.7	127.5	111.6	112.3	140.4	159.9	142.6	86.5	64.8

4.3.1 Variability of temperatures and rainfall

a.) Extreme rainfall and temperatures distribution

Analysis of spatial variability of maximum temperatures for October to December and January to March showed increased trend in the seasonal temperature (Figure.17a&b). OND showed an increasing trend ($P<0.05$) of 0.01°C per season while JFM has 0.003°C per season. The increase during OND would increase water stress for the crops by increasing the rate of evapotranspiration at the beginning of the season when the soil is still bare. This would lead to crop failures especially in times when dry spells are prolonged. Analysis of extreme rainfall events was done to find the frequency of occurrence of these events. The characteristics criteria used for selecting these extreme events are given in Table.3a. Comparison of rainfall anomalies for Makhanga and Ngabu showed that Ngabu rainfall had more extreme variability than Makhanga as noted but big values of rainfall index. However, inter-annual variation was clearer in between the two stations.

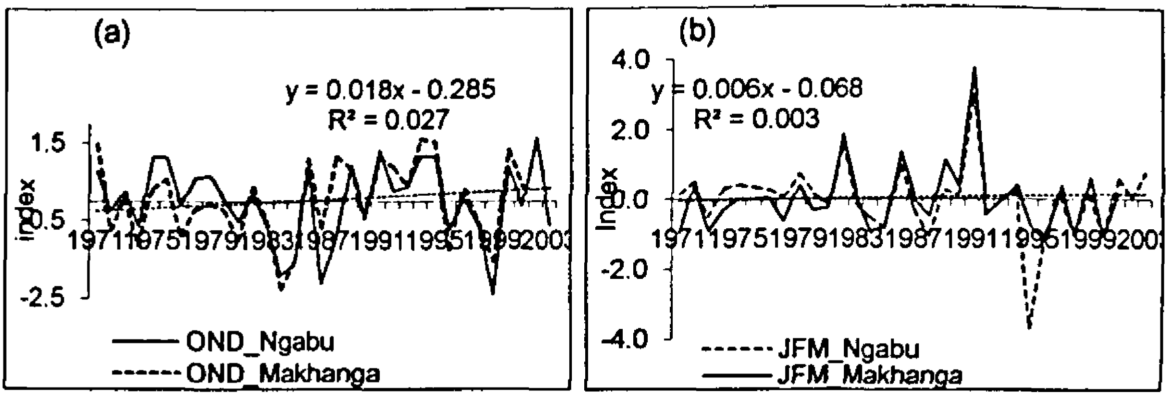


Figure 15: shows comparison of Makhanga and Ngabu temperatures anomalies for (a) OND and (b). JFM.

Since crop production is dependent of seasonal rainfall, in this study, the criteria used to analyse extreme events was done by considering total rainfall of OND and JFM. The characterized extremes of rainfall years were grouped into 15 years groups and the results showed that extreme events have increased over the present 15 years when compared to the previous consecutive groups (Table.3b). The results for characterisation of extreme rainfall years Table.3 showed that normal rainfall years have significantly decreased while numbers of wet years have increased over Makhanga and Nchalo but decreased over Ngabu. 1975-1989 periods were wetter than all the other years and Ngabu was wettest among all the station. Overall results showed that 1994-2004 was the wet period among the rest of the years with 22 wet years while 6 of these years were extremely wet.

Stations showed differences in variability magnitudes by a number of years a station wet and drier event had. Nchalo in total experienced more dry and wet years than any other station in the area (Figure.16). Makhanga had more dry years during the OND season than JFM while Ngabu had decreased number of normal years than Makhanga. However, total number of wet years increased over Nchalo and decline over Makhanga. The reason for the difference between stations is attributed to the influence of Congo air mass and Tropical Cyclones in the Indian Ocean, particularly Mozambique Channel. When cyclone is in the Mozambique channel , it brings prolong dry conditions in the area when the cyclone is above 20°S and more rains once it moves below this latitude.

Table 3 (a) Criteria for selection of characterisation of extreme rainfall years (b) Variability of extreme rainfall characteristics in the Shire valley

Table.3a shows criteria used for selection of characterisation of extreme rainfall years

Criteria	**OND**	**JFM**
Extremely wet years	Anomaly≥2.0	Anomaly≥2.0
Wet years	1.0≤Anomaly≤2.0	1.0≤Anomaly≤2.0
Normal years	**-1.0<Anomaly<1.0**	**-1.0<Anomaly<1.0**
Dry year	-2.0≥Anomaly≥1.0	-2.0≥Anomaly≥1.0
Extreme dry year	Anomaly ≤ -2.00	Anomaly ≤ -2.00

Table.3b Shows total number of years for a particular extreme events in the Shire valley

	1960-74					1975-1989					1990-2004					2005-2011				
AREA	Very dry	Dry	Normal	Wet	Very wet	Very dry	Dry	Normal	Wet	Very wet	Very dry	Dry	Normal	Wet	Very wet	Very dry	Dry	Normal	Wet	Very wet
OND(NG)	0	3	11	0	0	0	0	9	6	0	1	5	9	1	0	1	1	6	0	0
JFM(NG)	0	1	12	1	0	0	3	9	2	1	0	2	9	4	2	0	1	5	1	0
OND(NCH)	0	2	8	5	0	0	4	9	2	0	1	4	8	5	1	0	1	3	3	0
JFM(NCH)	0	2	12	1	0	1	4	8	3	1	0	2	8	5	1	0	1	6	0	0
OND(MK)	0	1	10	2	1	0	1	12	2	0	1	4	8	2	1	0	1	3	3	0
JFM(MK)	0	1	12	1	1	0	1	13	1	0	0	2	8	5	1	0	1	6	0	0
Total	0	10	65	10	2	1	13	60	16	2	3	19	50	22	6	1	6	29	7	0

The summary for the results were given by Table.3b. Figure.15a.and b shows more dry years during JFM than OND, JFM experienced very dry conditions than OND in Figure.15b. A plot of analysed daily extreme events for the region (Figure. 16) showed an increase in dry days at Nchalo and the central part of the region during OND, a southward shift was observed during JFM. Nchalo rainy days exceed any station while Chikwawa indicated to be the least affected area as shown by the mean rainy days ≥1mm in tables (4a-d). Nchalo also revealed a short fall in rainy days of greater magnitude suggesting that light rains dominate the area. In Table.4, number of rainydays for Nchalo were 14.5days for (≥15mm), 10.3days for (≥20mm) and 5.9 for (≥30mm) days in a year while for Ngabu were 16.6 For (≥15mm), 12.6 For (≥20mm) and 6.7 for (≥30mm).

Decrease in number of rainy days in the Shire valley is a very big threat to crop production. Since agriculture sorely depends on rainfall, climate variation has become a constant threat to the community. The results of the analysis have shown that numbers of dry days are increasing as rainfall continues to decline, threatening the socio-economy of the area. Although Sorghum is a drought tolerant crop, research has shown that variation in temperature, day light and rainfall affects its production, *(Wayne et.al. 2000)*. For this reason, increase in variability poses a very serious threat to its production. Summary statistics of Table 4, revealed evidence of instability in the variability of number of rainy days of threshold >30mm per day in a year as indicated by increase in COV in Table.4d.

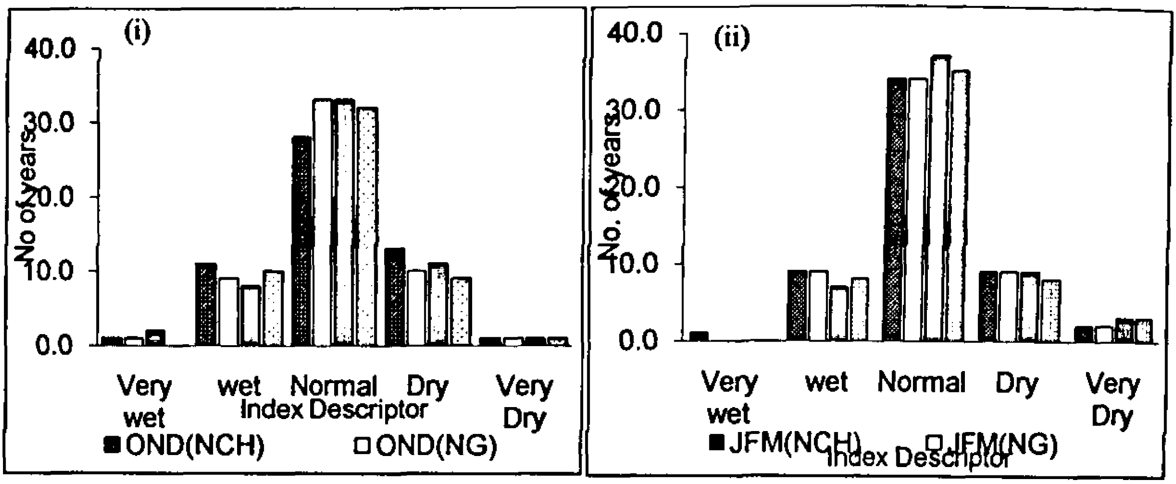


Figure 16: Showing extreme events for (a) OND and (b) JFM at Makhanga and Ngabu

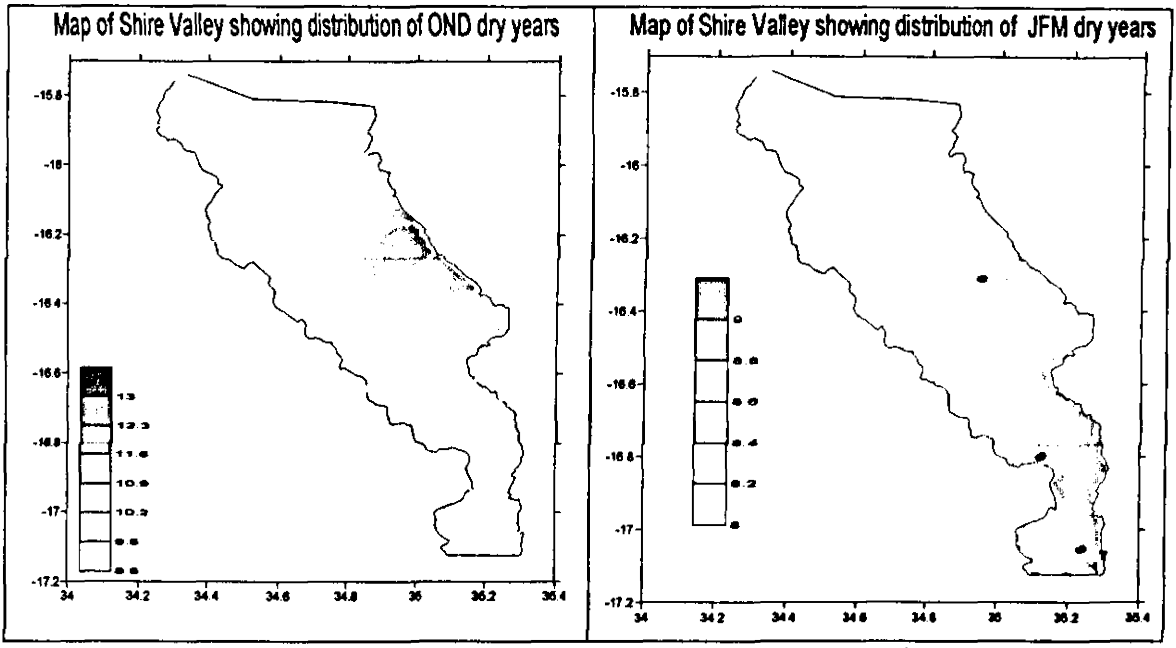


Figure 17: Spatial variability showing number of years with consecutive dry days.

Table 4 Summary of number of rain days with a given threshold in a year

Table.4a	*Ngab_rainydays >15mm*	*Ngab_rainyadays >24mm*	*Ngab_rainyadays >50mm*
Mean	16.3	12.4	2.4
Standard Deviation	5.22	4.20	1.64
Sample Variance	27.23	17.63	2.69
Minimum	5.0	4.0	0.0
Maximum	29.0	22.0	6.0
Count	50.0	50.0	50.0
CV	0.3	0.3	0.7
Conf. Level(95.0%)	1.48	1.19	0.47

Table 4b. Summary of No. of rainy day with daily rainfall ≥15.0 mm in a year

Indices	*Chikwawa R≥15mm*	*Makhanga R≥15mm*	*Nchalo R≥15mm*	*Ngabu R≥15mm*
Mean	16.2	15.2	14.5	16.6
Standard Deviation	5.4	5.4	4.2	4.9
CV(%)	**33.1**	**35.7**	**28.9**	**29.4**
Sample Variance	28.7	29.4	17.5	23.8
Minimum	2	2	6	8
Maximum	26	26	25	29
Count	51	51	40	51
Conf.Level(95.0%)	1.51	1.52	1.34	1.37

Table 4c. Summary of No. of rainy day with daily rainfall ≥20.0 mm in a year

Table 4c	*Chikwawa R≥20mm*	*Makhanga R≥20mm*	*Nchalo R≥20mm*	*Ngabu R≥20mm*
Mean	11.7	10.9	10.3	12.6
Standard Deviation	4.1	4.7	3.3	4.1
CV(%)	**35.3**	**42.8**	**32.1**	**32.7**
Sample Variance	17.1	21.9	10.9	17.0
Minimum	1	1	3	5
Maximum	21	23	21	23
Count	*51*	*51*	*40*	*51*
Conf. Level(95.0%)	1.16	1.36	1.06	1.16

Table.4d. Summary of No. of rainy day with daily rainfall ≥30mm in a year

Table.4d.	*Chikwawa R≥30mm*	*Makhanga R≥30mm*	*Nchalo R≥30mm*	*Ngabu R≥30mm*
Mean	6.3	6.4	5.9	6.7
Standard Deviation	3.19	3.22	2.56	3.49
CV(%)	**50.9**	**50.1**	**43.4**	**51.7**
Sample Variance	10.15	10.37	6.55	12.15
Minimum	0	0	1	2
Maximum	14	14	14	16
Count	51	51	40	51
Conf. Level(95.0%)	0.90	0.91	0.82	0.98

Number of rainy days for a given threshold at Ngabu depicted significant variability in the number of rainydays. An increase in total number of rainydays with rainfall amount >50mm were plotted. The graph showed an increasing trend in numbers of days from 1981 to 2008 which suggest increase in the number of days with extreme rainfall The series was further plotted taking into consideration a break point 1992 (a devastating El Niño year), the results showed a negative trend (Figure.19).

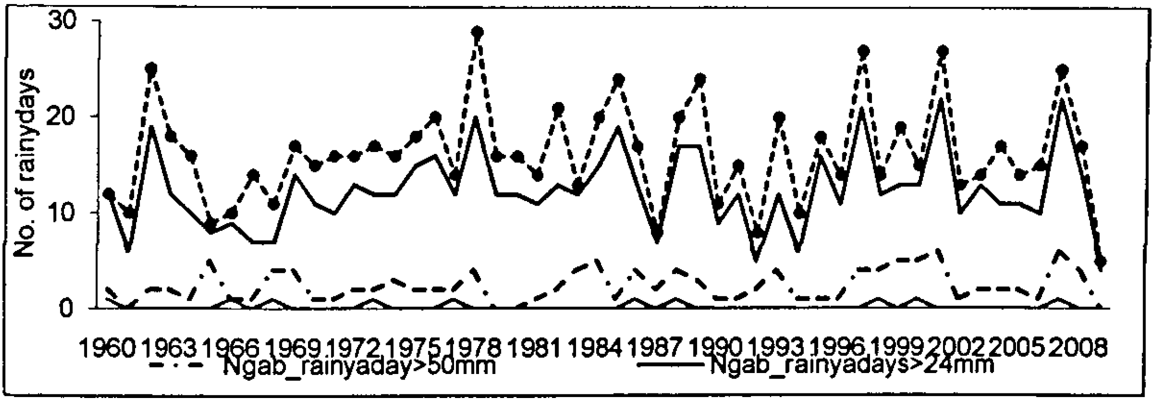


Figure 18 Annual variability of number of rain days at Ngabu Meteorological Station

Other stations in the areas have shown a decreasing trend in the number of rainy days which agrees with findings from Ngabu stations after the data sets was splits into two parts. *IPCC,* *(2007)* found that the decrease in rainfall is often attributable to a reduction in the number of rain days rather than the intensity of rain when it occurs. This reduction in rain days leads into reduction of growing period thereby putting pressure to crops production.

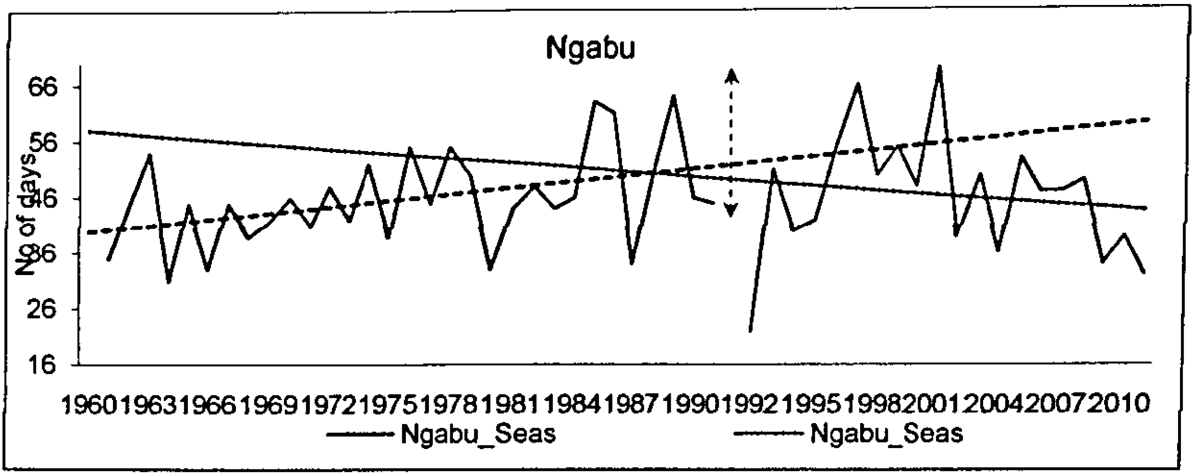


Figure.19: Seasonal variability in the number of rainy days

Table 5 Summary of extremes indices trends for study sites in the Shire Valley.

Station	TX10p	TX90p	TN10p	TN90p	WSDI	CSDI	R20mm	R0.5mm	CDD	CWD
Ngabu	-0.05	0.01	-0.20	0.07	0.12	-0.08	0.01	-0.08	0.68	-0.02
Makhanga	-0.14	0.15	-0.37	0.08	0.18	-0.16	0.10	-0.20	0.00	0.05

Note Tn10p, Tx10p 10th percentile of Tmin, Tmax centred on a 5-day window; Tn90p, Tx90p 90th percentile of Tmin, Tmax centred on a 5-day window; WSDI Hot spells (number of days); CSDI Cold spells (number of days); CDD(Number of days with 6 consecutive dry days); CWD (Number of days with 5 consecutive wet days).

Table.5. above gives an overall picture of climate variability in the Shire Valley which showed a significant increase in hot spells (WSDI) and a significant decrease of cold spells (CSDI) at Makhanga (significance tested using Cox-Stuart Test in Table(14a)). Maximum temperatures at 90^{th} percentile (TX90p) and minimum temperature (TN90p) has increased significantly. A decrease in extreme cold days (TN10P) at all sites. The 10th percentiles of maximum (TX10p) and minimum temperature (TN10p) have decreased significantly. The numbers of days with 6 consecutive dry days (CDD) have increased over Ngabu while remain stable at Makhanga. Makhanga also showed an increase in the number of wet days as opposed to Ngabu. This could be attributed to an increase in the frequency of tropical cyclone passing in the Mozambique Channel since Makhanga is less than 500km from the Mozambique coast.

The box plot results in the appendix also showed variability of consecutive wet and dry days (CWD, CDD) for the areas. The results affirm that Makhanga had more wet days in summer season than Ngabu. In the analysis it was also shown that Makhanga had longer period of cold spells than Ngabu. The reason to the difference is attributed to the geographical location of

Makhanga to moisture sources (Chiperoni and cyclones), attitude, as it is located at ascent point of the Shire highland. Table.6 shows statistical summary of extreme events.

Table 6 Statistical summary of extreme events in the Shire Valley

	MK-CWD	Ngab-CWD	Ngabu_CSDI	Makhanga_CSDI	Makhanga_CDD	Ngabu_CDD
Mean	6.8	6.3	3.2	4.3	65.9	68.6
Stdev	2.54	1.60	5.60	6.11	27.07	32.52
CV(%)	37.3	25.6	175.8	141.6	41.1	47.4

Since variability depends on the type of climate and the length of the considered period. The total annual rainfall at Ngabu, Makhanga, Chikwawa and Nchalo were plotted and the results show inter-annual variation in the data series (Figure.20). The study also revealed that numbers of days with rainfall amount of certain daily thresholds varied in frequency of their occurrence. Rainfall ≥10mm was declining (-0.003day/year) and that of rainfall ≥25mm is increasing (+0.06day/year), Figure.21.

Heavy rainfall had a considerable increasing trend (+0.063day/year) which showed that the frequency of extreme rainfall was increasing. This suggests that, although total numbers of rainy days are decreasing, there exist an increasing trend in the heavy rains which is consistent with IPCC findings (*IPCC, 2007*). *IPCC's* findings indicated that there is a tendency for an increase in daily heavy rainfall events in many regions, including some in which the mean rainfall is projected to decrease.

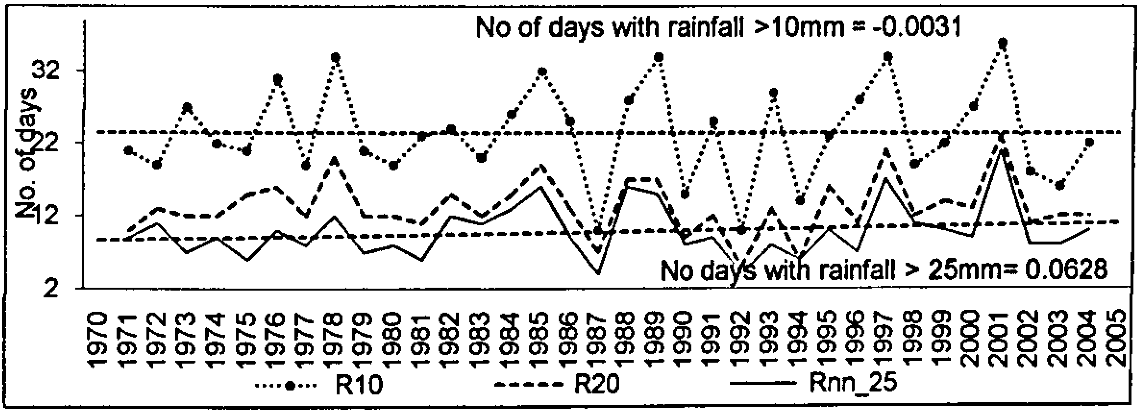


Figure 20 Comparison of number of days with daily rainfall (mm) for a given threshold

Analysis of historical daily rainfall extremes has also revealed incidence of increasing trend in the extreme events over Ngabu but were showing decreasing trend at Makhanga and Nchalo (Figure.21). The percentage increase in frequency was much larger for very heavy rainfall (>50mm per day), than in rainfall intensity such that the shift was toward increased heavy rainfall.

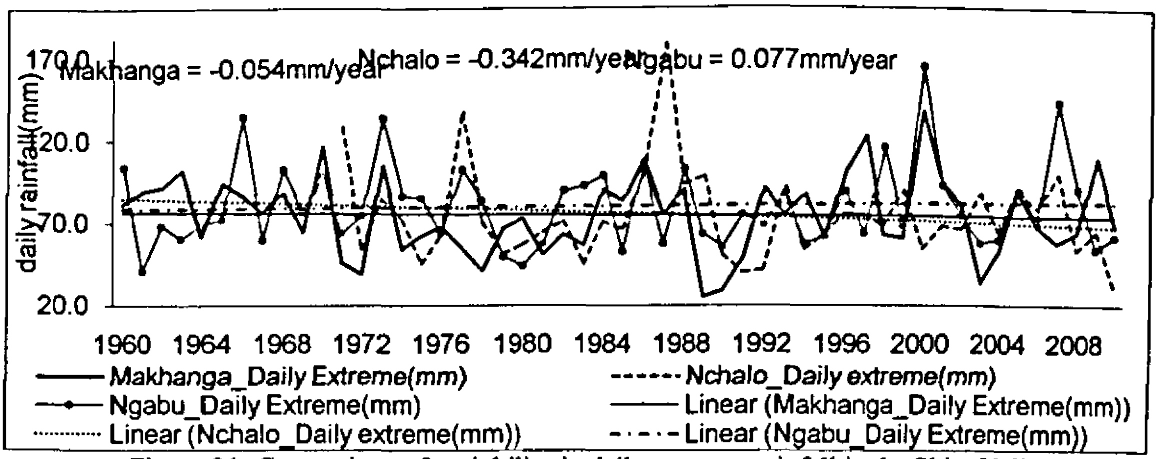


Figure 21: Comparison of variability in daily extreme rainfall in the Shire Valley

4.3.2 Monthly temperatures and rainfall variability

Variation of monthly temperature was also analysed and compared, the results showed similarities between Ngabu and Makhanga although each station showed significant intra-annual variations. Maximum temperatures were warmer at Ngabu between August and December while over Makhanga the warming was between April and May (Table.7b and c). However, Ngabu minimum temperatures were warmer than those of her counterpart Makhanga.

Coefficient of Variation (COV) was an accurate measure used to assess rainfall variability in the area than annual average rainfall as it showed the natural year-to-year variability. Higher valued of COV indicated a greater degree of rainfall variability on a year-to-year basis over each station (*Schulze 2006*). All stations revealed existence of variability in the daily, monthly and seasonal rainfall variation. The magnitude of variations in rainfall was accessed by plotting COV graph and maps (Figure.22) for all the station. Temperatures showed stable variance as shown by low COV in Table.7d. COV here was used to statistically measure the potential intra-seasonal, inter seasonal, inter-annual fluctuations in rainfall availability. Increased climate variability was shown by larger year-to-year fluctuations, a higher COV implied less predictability in the climate. Monthly temperatures for Makhanga and Ngabu showed more variation in the month of January to March while rainfall pattern over Makhanga showed more variation in the month of February than any other station.

Table 7 Statistical summary of maximum and minimum temperatures for Makhanga and Ngabu stations.

Table.7a. Ngabu Minimum temperatures (overall mean)-1971-2004

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	25.8	24.9	24.9	23.9	21.4	19.5	19.4	21.0	23.8	26.4	27.4	26.9	23.8
stdev	1.570	1.326	1.027	1.102	1.401	1.354	1.194	1.324	1.343	0.984	1.063	1.174	0.88
CV(%)	6.1	5.3	4.1	4.6	6.5	6.9	6.2	6.3	5.6	3.7	3.9	4.4	3.2

Table. 7b. Ngabu Maximum temperatures (overall mean)-1971-2004

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	37.4	36.4	36.2	35.9	34.8	32.8	32.7	36.0	39.1	41.2	41.9	39.8	37.0
stdev	2.12	2.51	1.55	1.87	2.20	1.76	1.71	1.41	1.59	1.10	1.56	1.93	1.08
CV(%)	5.7	6.9	4.3	5.2	6.3	5.4	5.2	4.1	4.1	2.7	3.8	4.8	2.6

Table. 7c. Makhanga monthly maximum temperatures (overall mean) -1971-2002

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	37.5	36.7	36.5	36.3	35.3	32.8	32.7	35.7	38.8	40.8	41.4	39.4	37.0
stdev	1.67	2.02	1.45	1.92	2.24	1.82	1.94	1.49	1.48	1.55	1.86	1.91	1.50
COV	4.5	5.5	4.0	5.3	6.3	5.6	5.9	4.2	3.8	3.8	4.5	4.8	3.6

Table. 7d. Makhanga monthly minimum temperature (overall mean))-1971-2002

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	23.0	22.8	22.3	20.5	17.3	14.7	14.7	15.9	19.1	21.6	23.1	23.2	19.8
stdev	0.61	0.64	0.72	0.68	1.05	1.14	0.97	0.98	0.97	0.93	0.99	0.60	0.51
CV(%)	2.6	2.8	3.2	3.3	6.1	7.7	6.6	6.2	5.0	4.3	4.3	2.6	2.5

Figure.22 shows map of variability of rainfall in the Shire Valley. The northern part of the area showed increase in the variability during OND while JFM map showed a shift in the distribution of variability as more variation appeared south of the area. This agrees with the pattern of rainfall distribution in the areas whereby rainfall onset starts from the south and spread northwards. In addition to this from January into March, moist Congo air mass (Zaire Air mass) becomes established into the country hence the northern sector of the region becomes more advantaged.

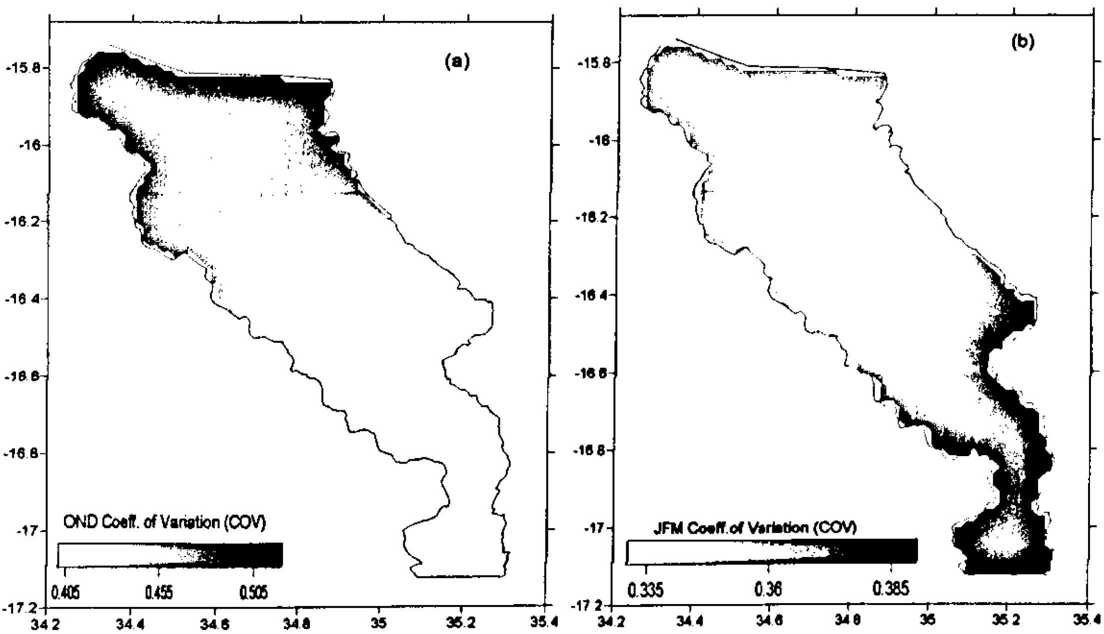


Figure 22: Coefficient of variation (COV) showing spatial distribution of rainfall in the Shire Valley.

Further comparison on long term means rainfall was done graphically on all the station and the results in monthly 30year rainfall and temperatures means affirmed variation shown in the extreme events as shown by a shift in the graphs peak (Figure.24a-b).

Distribution of rainfall in the Shire valley seemed to follows the geographical features of the area. The western side of the region where Kirk ranges are located, Khulubvi in Nsanje and Masenjere/Mkhathe in eastern bank receives more rains in both periods of the season than the central part. (Figure.3). Rainfall analysis revealed a change in variance at Ngabu and Makhanga but the variance remain stable over Chikwawa and Nchalo. Change in the mean rainfall was also observed over all the stations (30year intervals of 1961 to 2011) as shown by Figure.24.

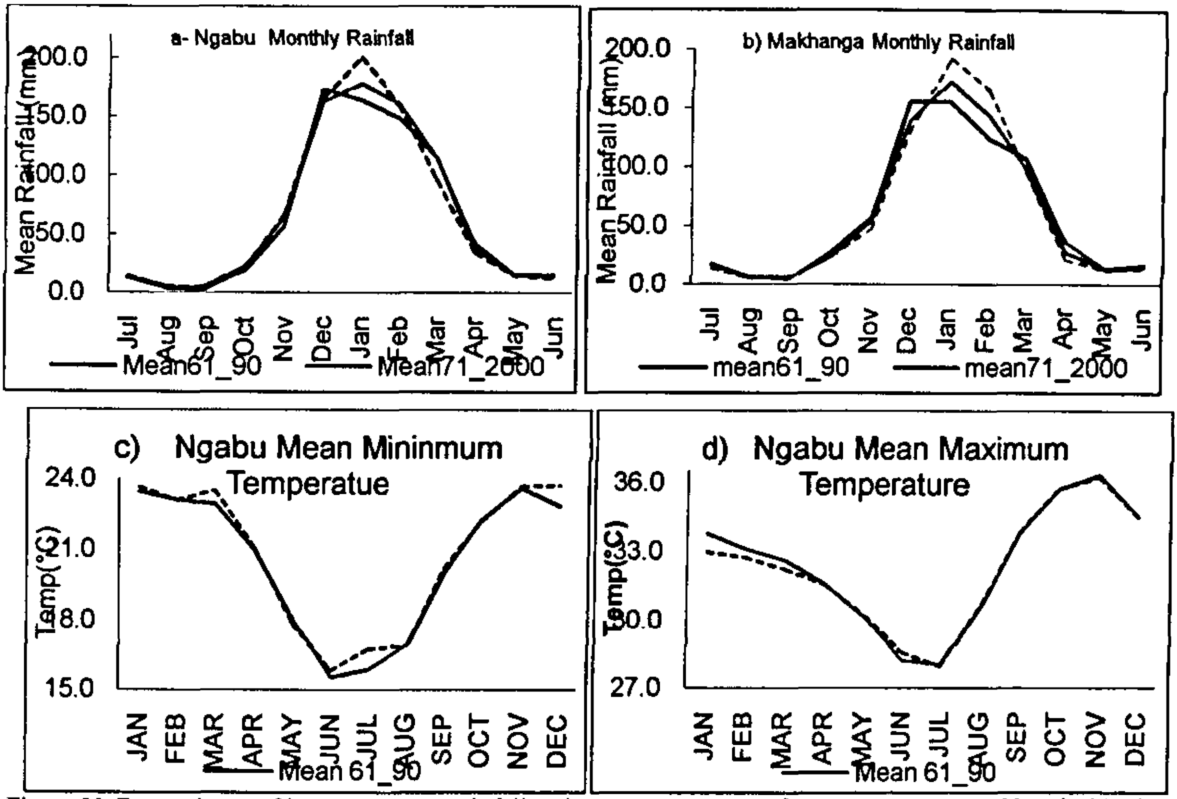


Figure 23 Comparisons of long term mean rainfall and mean temperatures for 1961-90; 1971-2000 and 1981-2011 from Ngabu and Makhanga

Temperatures show monthly mean variation in all the stations. Minimum temperatures are generally increasing in all months for all the stations. Maximum temperatures over Ngabu show a mean decrease during summer (Oct-April) while warming in winter (May to August) Figure.23. The analysis also revealed that for the past 30 years, Ngabu has experienced an increase mean monthly minimum temperatures of 0.2°C and a decrease maximum temperature of -0.1°C. Likewise, Makhanga experienced an increase of 0.05°Cand 0.2°C in minimum and maximum temperatures respectively. The cause for this night time warming in the observed temperatures has been attributed to warming in the nocturnal boundary layer due to a redistribution of heat and warming due to the accumulation of heat.

According to *McNider et al., 2010; Brito-Castillo, 2009*, competition between thermal stability and mechanical shear contributes to the differences. If there is stability in the atmosphere then turbulence is suppressed leading to cool surface and warmer air aloft. If shear is greater than stability, then there is turbulence which results into warmer air from aloft continually mixed to the surface. This causes a significant lower cooling rate that lead to warmer temperatures due to heat redistribution. Other likely causes can be attributed to increases in atmospheric water vapor, changes in greenhouse gas forcing, surface roughness, cloudiness, and surface heat capacity (including soil moisture). Following *IPCC, (2001)* report, rainfall is one of the climate variables that are poorly approximated by normal distributions. As such identifying variability in the data series becomes difficult. However, analysis of 10 year mean rainfall from the study sites showed significant monthly mean variation over the region as shown by shifts in peak-month and total mean rainfall Figure.24.

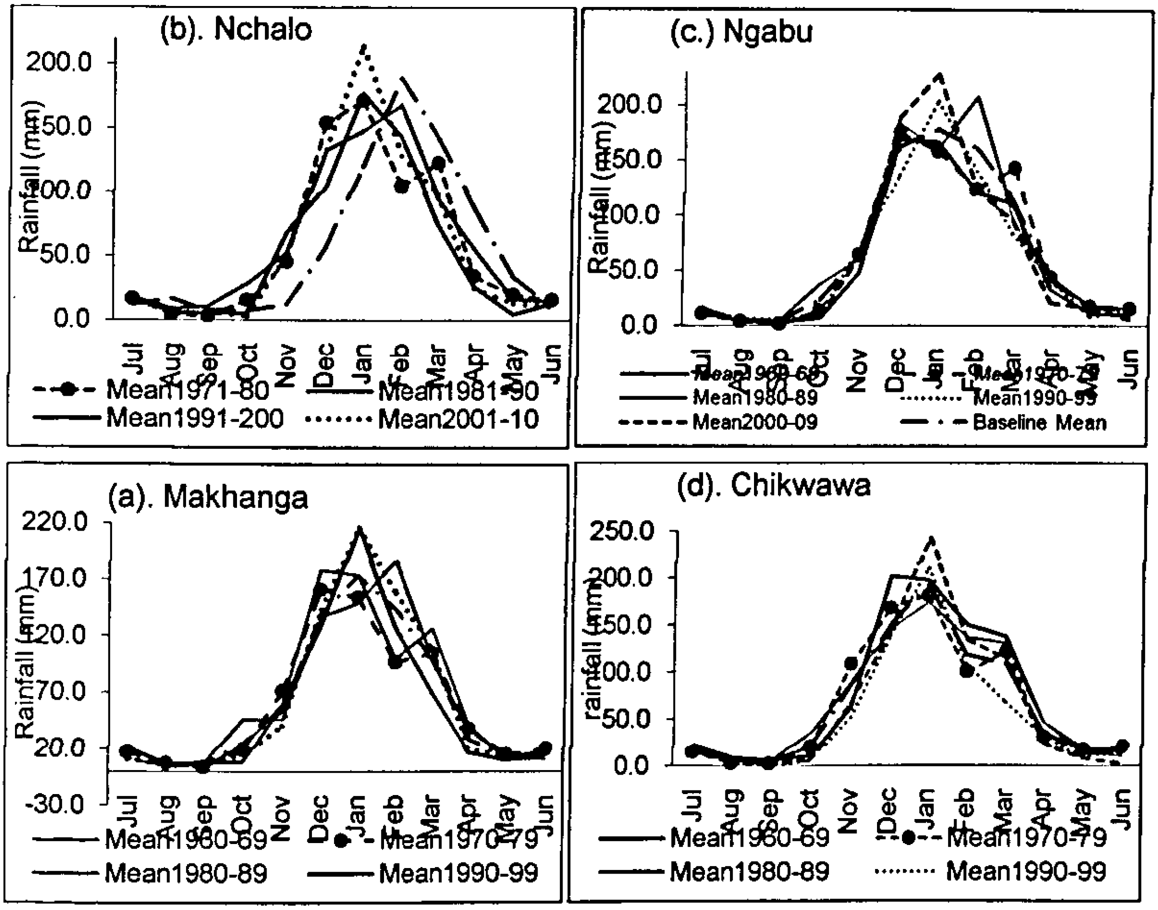
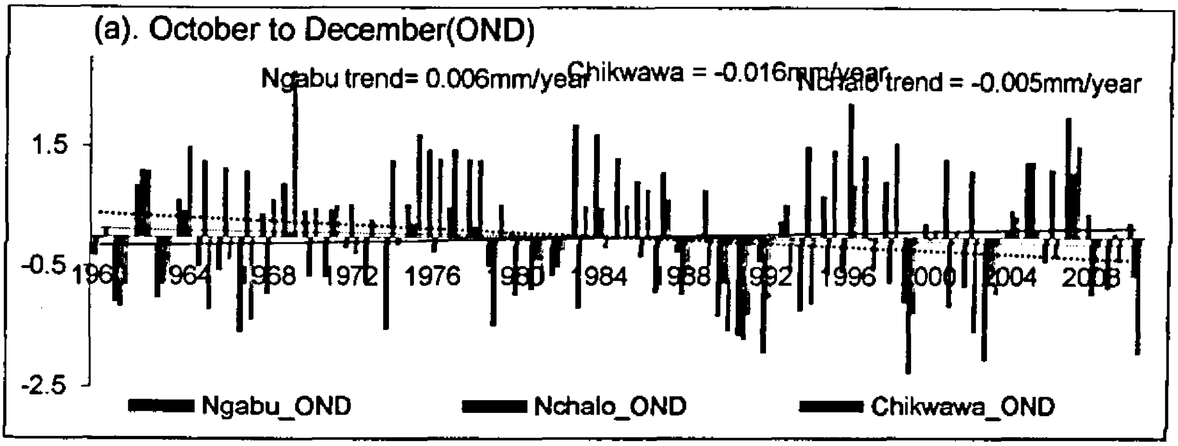
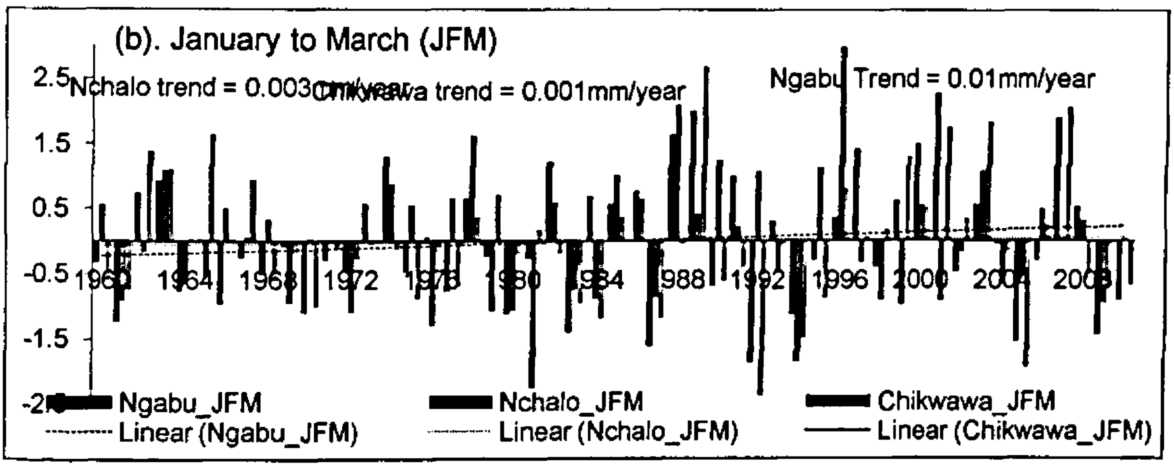


Figure 24 Comparisons of 10year mean rainfall against baseline (1971-2000) for (a) Nchalo, (b) Makhanga, (c) Ngabu and (d) Chikwawa.

Analysis of anomalies for the study sites showed that OND rainfall decrease over most stations except for Ngabu where an increase was observed (Figure.25a). Mean rainfall (Oct-Mar.) for all the stations exceeded 600mm during summer; but for JFM alone were 400mm and over 200mm during October to December (OND). January to March rainfall showed increasing trend although, annual rainfall trend in the areas was decreasing. It was also found that January and February were the month when the stations receives a lot of extreme rainfall events leading to increased mean rainfall or droughts.

Analysis of JFM rainfall disclosed decreasing trends in most of the station, (Figure.25b). Ngabu seasonal rainfall was plotted for ENSO episodes. The results indicate more rains are experienced during neutral years followed by La Niña years (Figure.26). During El Niño years there is a tendency of rains to be below normal. This is in agreement to what Jury and Mwafulirwa, (2002) observed in their study. Relating Figure 26 and 25, it was shown that during ENSO years, El Niño has a negative influence over rainfall in the study area.





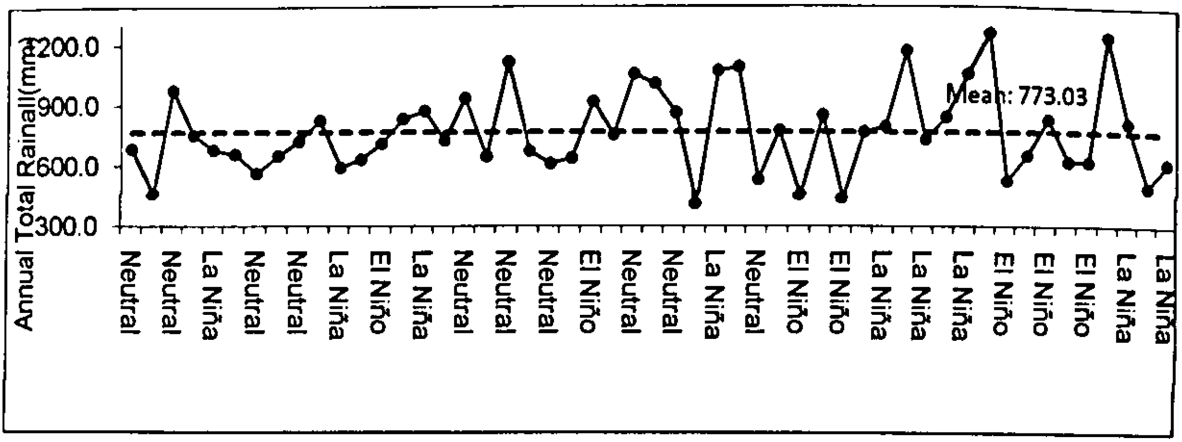


Figure 25 Shows Seasonal rainfall anomalies for (a) OND and (b) JFM from Nchalo, Ngabu and Makhanga in the Shire Valley and (c) ENSO episodes in relation to rainfall distribution from 1960 to 2010 at Ngabu

A general comparison of all the station (Figure.26) showed year to year varaiation of seasonal rainfall between stations. This asserts the fact that rainfall distribution siginificantly varies from one point to another even if stations are few kilometers apart.

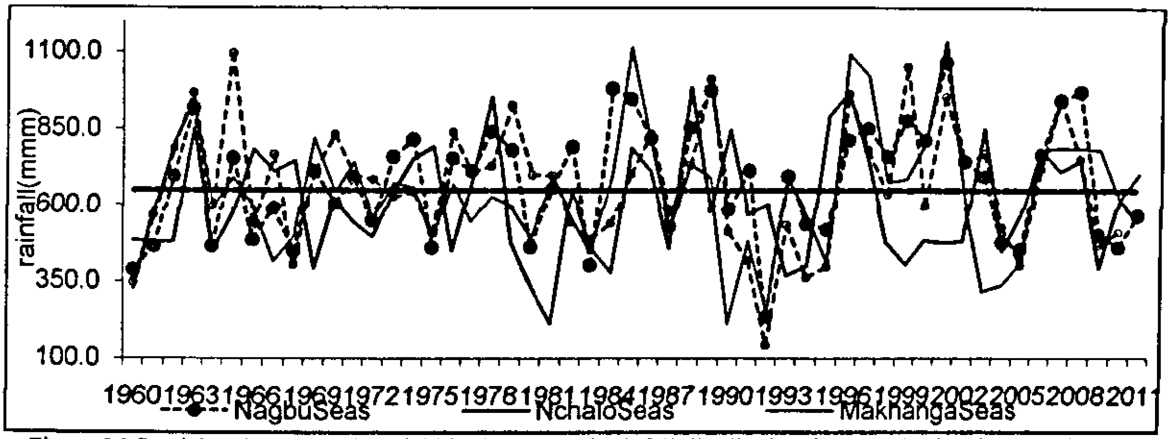


Figure 26 Spatial and Temporal Variability in seasonal rainfall distribution from study sites in the Shire Valley (1961-2011)

In Figure.26 examination of the time series did not reveal any trend. Therefore, the data sets were then divided into two sub-sets to represent the two long term means of the time series 1961-1990 and 1971-2000. F-test, and t-test were evaluated for the sub-sets and the results are given in Tables 8 and 9. The results revealed that there were unstable variances which implied that there was change in the mean rainfall as calculated *t* lies in the critical region. Therefore, the difference between the means of the sub-sets; 751.2mm for Sub-Set A and 794mm for Sub-Set B for Ngabu rainfall, and mean of maximum temperatures 32.4 for Ngabu. For Chikwawa, mean rainfall of 808.4mm for Sub-Set A and 762.0mm for Sub-Set B, Makhanga mean temperatures 32.2 (19.3) °C and 32.8 (19.9)°C for maximum (minimum) are real at the 5% level of significance. The time series for both temperatures and rainfall showed a general positive increase around 1980 hence they are not stationary. F-test and t-test for stability of variance and stability of mean respectively were also applied to the time series of rainfall from Chikwawa, Makhanga, Ngabu and Nchalo, while temperatures was only from Ngabu and Makhanga.

Table 8: Computation of F, and t, for Ngabu and Makhanga Seasonal rainfall (mm) from 1960 to 2011

Table.8	Ngabu		Makhanga		Chikwawa		Nchalo	
Data	Sample1	Sample2	Sample1	Sample2	Sample1	Sample2	Sample1	Sample2
Mean	751.2	794.0	728.3	734.3	808.4	762.0	733.3	680.4
Stdev(σ)	158.4	251.3	127.7	279.3	169.7	263.1	154.1	210.1
σ^2	25091.9	63159.4	16303.6	78014.7	28814.0	69228.9	23756.8	44135.8
		df		df		df		df
F-test	**2.519**	**25,26**	**4.785**	**25,26**	**2.404**	**25,26**	**1.859**	**20,20**
t-test	**-0.720**	**49**	**-0.098**	**49**	**0.740**	**49**	**0.908**	**38**

Table 9: F, and t, for two sub-sets of Ngabu and Makhanga annual temperatures (°C) for (1971- 2004

Table.9	Ngabu Max.Temp.		Ngabu Min. Temp		Makhanga Max.Temp		Makhanga Min.Temp	
Data	Sample1	Sample2	Sample1	Sample2	Sample1	Sample2	Sample1	Sample2
Mean	**32.4**	31.8	**20.3**	21.4	**32.2**	**32.8**	**19.3**	**19.9**
Stdev(σ)	2.94	2.35	3.27	3.01	2.90	2.656	3.46	3.2
σ^2	8.639	8.290	10.689	9.061	8.392	7.0538	11.951	10.340
F-test	1.043		1.099		1.190		1.160	
t-test	0.243		-0.939		-2.113		-1.862	
F-tabulated	2.40		2.40		2.40		2.40	
T-tabulated	1.697		1.697		1.697		1.697	

The values of F, and t, tests for two sub-sets are given in Table.8 for rainfall and Table.9 for temperatures. The critical values come from the tables of percentile points of the F-Distribution. The values of tabulated F in Table.8 support significance of instability in the variance at 95% level of significance. The pooled estimates of the variances were used to do the t-test for stability of mean. The results also show that there is a significant difference between mean of monthly temperatures in sample A and sample B over Makhanga. This showed there exist a temporal variability in monthly temperatures as shown by calculated P= 0.032 and 0.033 are less than p=0.05 two tailed test.

4.3.3 Seasonal rainfall Variability

Rainfall was grouped into months related to the season pattern of the study area. October to March is the wet period where most rain-fed agricultural activities are done. However, January and February are the crucial month for the growth of crop in the study area. When the area experiences dry spells for over 2 weeks in a maize crop and more than that for sorghum, the yield output for that season get affected as well. Seasonal rainfall was categorized in the following categories; January to March (JFM), October to December (OND) and October to March. Rainfall for the region was summarised statistically and the results are shown in

Table.10. Analysis of dekadal rainfall showed Nsanje and Nchalo to be wet than Makhanga and Chikwawa and Ngabu. Wetter conditions were experienced at Chikwawa and Nsanje between November and February as shown by Table.39 in the appendix.

From Table.10 rainfall over Makhanga and Chikwawa shows more variability than Ngabu and Nchalo for both JFM and OND. This showed that the areas experienced more unstable rainfall distribution than the other two stations. Most likely reason for increase in variability apart from geographical and altitude factors are that Makhanga is close to the Tropical Cyclone path while Chikwawa is close to Congo air mass path. October to March (alternatively OA) rainfall had some stable variation over Nchalo but showed variability in the mean rainfall over Makhanga as shown in the Table.11. A careful look at temperatures from Ngabu showed increase in minimum temperatures (exceed that of Makhanga by 0.3°C) and maximum temperatures for Makhanga are higher than that of Ngabu.

Table 10:Table 10 Statistical summary of Seasonal rainfall variability. (n=52 and n=40 for Nchalo)

OND	min	max	mean	SE.mean	CI.mean.0.95	var	std.dev	coef.var
SVRadn	15.9	23.3	20.8	0.472	0.99	4.449	2.109	0.10
NGABU.OND	45.6	418.4	241.3	24.84	52	12343.13	111.1	0.46
CK.OND	42.3	451.6	216.7	29.222	61.2	17078.81	130.686	0.60
NCH.OND	30.3	323.5	176.8	18.97	39.7	7193.98	84.82	0.48
MK.OND	39	411.5	200.0	25.49	53.4	12999.2	114.01	0.57
JFM	min	max	mean	SE.mean	CI.mean.0.95	var	std.dev	coef.var
NGABU.JFM	146.6	794.5	489.51	40.091	83.9	32144.973	179.29	0.37
CK.JFM	68.1	857.9	457.64	43	90	36978.97	192.3	0.42
NCH.JFM	102.2	695	429.54	34.401	72	23668.785	153.847	0.36
MK.JFM	112.9	922.1	468.58	48.089	101	46251.602	215.062	0.46

Table 11: Statistical Summary of seasonal Rainfall from Shire Valley (1960-2011), (n=32)

	min	max	mean	SE.mean	CI.mean.0.95	var	std.dev	coef.var
Ngabu_OA	369	1182	771	56.34	117.91	63475.71	251.9	0.33
Chikwawa_OA	183	1077	712.9	58.39	122.22	68193.01	261.1	0.37
Nchalo_OA	266	901	647.0	41.37	86.59	34233.66	185.0	0.29
Makhanga_OA	183	1193	687.3	65.03	136.11	84578.72	290.8	0.42

Analysis of rainfall for the four stations in the area revealed that during JFM, Makhanga had more variation in the mean rainfall. Standard deviation for the period was 163.2mm with a mean rainfall of 418.6mm, and was less than any other station. During the months of October to December, Chikwawa showed more variation in the mean than the rest of the stations. Rainfall distribution for the whole season (October to March) showed unstable mean over Chikwawa. Summary of the mean rainfall and temperature are given in Table.10, 11 and 12. The distribution patterns of rainfall and temperatures demonstrated how climate elements such as rainfall vary for each station. These variations also revealed how each variable influence other dependent factors of interest such as soil moisture and final yield.

Table 12 Monthly temperatures summary for Ngabu and Makhanga

Descriptors	Ngabutmax	Makhangatmax	Ngabutmin	Makhangatmin
mean	**34.285**	**34.369**	**23.188**	**22.803**
SE.mean	0.15	0.126	0.094	0.095
CI.mean.0.95	0.305	0.257	0.192	0.194
var	0.763	0.509	0.302	0.289
std.dev	0.873	0.713	0.55	0.537
coef.var	0.025	0.021	0.024	0.024
Samplesize(n)	34	34	34	34

4.3.4. Trends in the rainfall and temperature variability

4.3.4.1 Test for Persistence

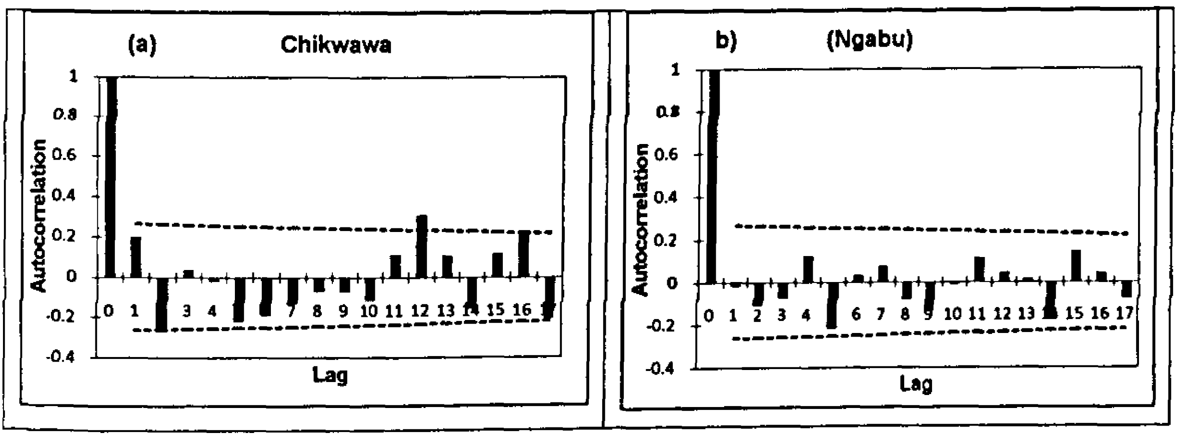
Table.13 depicts results of lagged correlation at r1, r2 and r3. The results show the lagged-correlation of variations in the monthly temperatures at the 2 stations (where average monthly temperatures were serially correlated with average monthly temperatures). The results showed statistically significant positive lagged-correlations (Table.13) at a confidence level at 0.05 for Makhanga and Ngabu stations. The results showed that temperatures varied closely between the two stations. The 1-month lagged-variations of the annual average temperatures depicted a fairly lagged relationship between the variations in maximum temperatures for Makhanga and Ngabu. The very close relationships of variations between the two stations suggest the conditions influencing temperatures particularly maximum temperatures are the same. However, minimum temperatures showed a strong relationship than maximum temperatures. The relationships between the two stations showed that variation in temperatures is caused by similar factors. These results also suggest an insignificant effect of altitude on temperature variation between the two stations. In all the station, calculated t was larger than the t critical boundary justifying the significance of the correlation between two consecutive observations and evidence of persistence characterized by a positive serial correlation. The data also revealed that time series were not completely random as the population auto-correlation function was not equal to zero for all lags (Figure.27).

Table 13: Summary of lagged Auto-correlation coefficients for Temperature at Ngabu and Makhanga

Ngabu	**r1**	**r2**	**r3**
Ngabu_tmax=	0.706	0.287	-0.129
Ngabu_tmin=	0.772	0.391	-0.059
Ttest-tmax	20.101	6.037	-2.629
tcrit.	*-0.966<tcrit<0.966*	*1.966<tcrit<1.966*	*-1.966<tcrit<1.966*
Ttest-tmin	24.469	8.555	-1.182
tcrit.	-0.966<tcrit<0.966	1.966<tcrit<1.966	-1.966<tcrit<1.966
$(rL)_{1.965}$	-1.1714 < r1 < -0.829	-1.1740 < r2 <- 0.826	-1.177<r3<-0.823
Makhanga_tmax=	0.690	0.282	-0.127
Makhanga-tmin=	0.803	0.415	-0.054
Ttest-tmax	19.189	5.912	-2.587
tcrit.	-0.966<tcrit<0.966	-0.97<tcrit<1.97	-0.97<tcrit<1.97
Ttest-tmin	27.119	9.197	-1.081
tcrit.	-0.97<tcrit<0.966	-0.97<tcrit<1.966	-1.966<tcrit <1.966
$(rL)_{1.965}$	-1.177 < r1 < -0.823	-1.180 < r2 <- 0.820	-1.182<r3<-0.818

Temperatures and rainfall data series was made serially independent by grouping the data sets into sub-groups representing seasonality. Box-Cox and Loess transformation was applied to remove seasonal influence in the series. The de-seasoned results is shown in Figure.28.(a-c). The results of de-seasoning indicated that influence of seasonality was eliminated in the data sets. This helped to detect the trend of climate variability without influence of other factors. The de-seasoned series was then subjected to Mann- Kendall tests for trend analysis.

The relationship between the correlogram and spectral estimates for sample time series of monthly rainfall in the Shire Valley are shown in Figure.27. Persistence in the time series was shown by the change in the spectrum over all the wavelengths. The amplitude of the spectrum (Figure.27d) was a red noise and showed a decreasing trend from long to short wavelengths (i.e. corresponding to increasing order of lags).



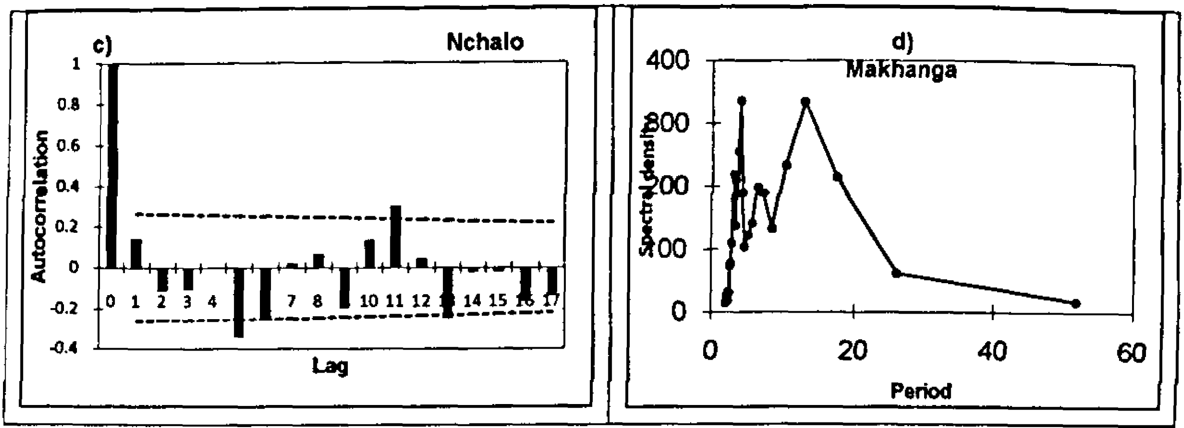


Figure 27 (a-c) Plots for lag 1 which gives the seasonal distributions pattern of lag-1 to lag-3 serial correlation coefficients for the considered variables in the Shire Valley. (d) Shows spectral series with persistence (red noise).

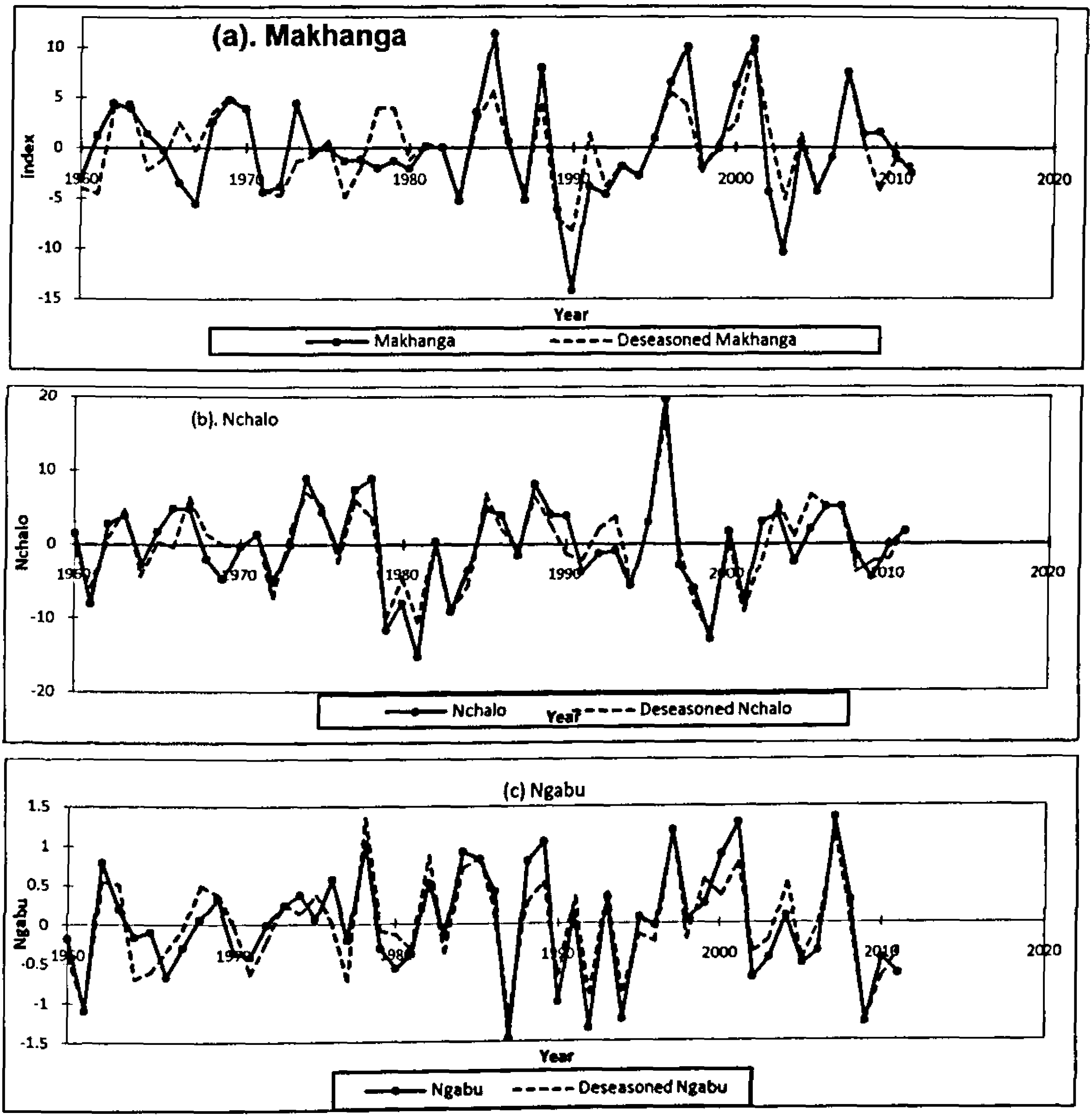


Figure 28: Rainfall time plots (blue) fitted with a de-seasoned series (red) for (a) Makhanga, (b) Nchalo and (c) Ngabu

4.3.4.2 Trends in Monthly rainfall variability

Negative trends dominated the monthly series in both cases where the Mann Kendal test was applied directly first to the series and after this de-seasoned series were subjected to Seasonal Mann Kendal. Three of the four sites stations showed a positive trend in temperatures. Out of these 3 positive trends none showed significant trends. On the other hand, all the four stations showed negative rainfall trends, with only one station, Makhanga, having a significant trend at the 5% significance level (Tables 14.).

Table 14 Slope and test statistics of Climate variable with Mann Kendal test

Ngabu			**Makhanga**			**Chikwawa**	**Nchalo**
Rainfall	Tmax	Tmin	Rainfall	Tmax	Tmin	Rainfall	Rainfall
Slope-0.349	-0.00342	**0.0167**	**-0.135**	0.0215	0.020	-0.0740	**-0.0883**
Tau -0.024	Tau -0.008	Tau0.046	Tau-0.062	Tau0.052	Tau0.055	Tau-0.052	Tau-0.040
S = -3031. z = -0.812 p = 0.4166	S =-639. z =-0.232 p =0.816	**S =3780. z =1.373 p =0.1696**	S = -7628. z = -2.057 p = 0.0397	S =3822. z =1.521 p =0.1284	S = 4044. z = 1.609 p =0.1076	S = -6235. z = -1.716 p = 0.0861	S = -4605. z = -1.312 p = 0.1895

The spatial distribution of the trends was in a pattern where the whole region had all negative trends. When de-seasoned series were subjected to seasonal Kendal, rainfall series showed consistent temporal negative trends except Ngabu which had a positive trend. These trends were not significant at 5% except for Makhanga which was consistent with the first findings. Temperatures were significantly decreasing at all the stations with Makhanga tallying in the rate of increase in both minimum and maximum. A summary of seasonal Mann Kendall is given in Table. 15. Likewise, analysis of climate extreme events was done and the finding subjected to Mann Kendal test.

Table 15 Slope and test statistics of Climate variable with Seasonal Mann Kendall test

Ngabu			**Makhanga**			**Chikwawa**	**Nchalo**
Rainfall	Tmax	Tmin	Rainfall	Tmax	Tmin	Rainfall	Rainfall
Slope=0.00	-0.311e-02	0.229e-01	-0.810e-01	0.250e-01	0.250e-01	0.000	-0.385-01
Tau -0.026	Tau=-0.017	Tau=0.192	Tau=-0.080	Tau=0.134	Tau=0.174	Tau=-0.061	Tau=-0.045
S = -248. z = -0.816 p = 0.4143 p*= 0.4498	S = -108 z = -0.476 p = 0.6338 p*= 0.7201	S =1208 z =5.388 p =0.000 p*=0.0011	S= -753 z=-0.500 p= 0.0124 p*= 0.048	S = 741 z = 3.610 p=0.0003 p*=0.0088	S = 966 z = 4.712 p = 0.000 p*=0.0064	S =-557 z =-0.916 p=0.0554 p*=0.1129	S = -394 z= -1.916 p= 0.1671 p*=0.2678

In seasonal Mann Kendal test statistics p* is adjusted p for correlation at 95% significance level among seasons which are serially dependent and was applicable for data series >10 years.

In Table.15 above 34 years monthly data records starting from 1971 to 2004 for temperatures and 1960 – 2011 for rainfall were re-analyzed using seasonal Mann Kendall test. The results of the analysis in Table 15 showed Makhanga temperatures and rainfall to be significant while over Ngabu, only minimum temperatures were significant. The results were also supported by analysis of Cox Stuart Test for trend analysis in Table.16.

From the results, it was revealed that maximum and maximum temperatures are significantly increasing except for Ngabu where maximum temperatures are showed a decreasing trend. Rainfall in the area depicted an insignificant decreasing trend except for an increase at Ngabu. Sorghum yield in the area showed an insignificant decreasing (p-value = 0.133) at 95% significance level. Table.16 shows the summary of the results. Crop water stress due to increasing eva-transpiration from excess temperature and low rainfall is more likely going to continue affect crop production thereby contributing to low yields as revealed by the results. Increase in temperatures combined with decreasing rainfall will affect future water balance hence crop metabolism. Since flowering of sorghum takes place early in the morning, with the projected increase in the minimum temperatures in the region, pollination of sorghum will be reduced and this would result into low yields.

The analysis in general showed increase in the variability of monthly temperatures and rainfall. The analyses also showed a general increase in minimum and maximum temperatures as rainfall trend was insignificantly decreasing. However, the rate of increase in temperatures in the areas is influenced by several factors including difference in altitude and land use due to changes in the environmental characteristics of the region. This is in agreement to studies done in the region which indicated that there was increase in climate extreme events, (*Ngongondo et. al., 2011, Tearfund, 2010; Nangoma, 2008*). From Table.13, it is evident that no stations showed insignificant serial correlation coefficient (SC) for climatic variables (rainfall, minimum and maximum temperatures). Monthly temperature and rainfall over Nchalo and Makhanga showed the existence of persistence characterized by significant lag-1 and lag-2 Serial Correlation; high frequency variability characterized by significant positive lag 1-SC (Figure.13) are also seen in temperature series from all the station except Ngabu where maximum temperatures are rising. The spatial distribution of lag 1- SC indicated the presence of persistence in temperature, which might be due to dependence of temperatures on altitude. The ACF plots showed that data series over Ngabu has a seasonal pattern as shown in Figue.13 where sixth and the twelveith months were the sink and peaks in the serial coefficents. Just like rainfall, temperature showed the same pattern. Variability in rainfall showed a significant correlation of Makhanga rainfall with $p<0.032$ while Nchalo, Ngabu and Chikwawa were insignificant. This implied that no sreial correlation exsted at these station hence as indicated by the increased in the number of days with extreme events and dry spells provided proof of existing threats to food security.

Table 16 Climate variable trends test using Cox-Stuart Test

TEMPERATURE			
Variable	**Trend type**	**Significance level**	**Significance**
Ngabutx	D*	p-value=0.5282	ins
Ngabutn	I*	p-value=1e-04	sig
Makhnagnatx	I*	p-value=4e-4	sig
Makhangatn	I*	p-value=0.0055	sig
RAINFALL			
Ngabu_RF	I*	p- value=0.1635	ins
Nchalo_RF,	D*	p- value=0.5775	ins
Makhanga_RF	D*	p-value=0.5775	ins
Chikwawa_RF	D*	p-value=0.2786	ins

In the table D*=decreasing trend, I*=increasing trend, ins =insignificant, sig=significant

4.4 Climate influence on sorghum production in the Shire Valley.

4.4.1 Results from correlation between climate elements and Sorghum Yield

To find the effect of present climate variability on sorghum yield, Pearson correlation coefficient and regression analysis were used. The observed climate variables and sorghum yields were compared and plotted against yields for two growing zones (Nsanje EPA and Chikwawa EPA) in the Shire valley. The results showed that yield variability followed the pattern of rainfall variability. Results from the correlation of climatic elements to sorghum showed that all elements had a significant effect on sorghum yield at $p < 0.05$. The relationship was revealed by a high correlation coefficient values. Maximum temperature, radiation and rainfall showed that they are the most influential factors in the study sites as shown by the correlation coefficients presented in Table.17.

This finding also indicated that minimum temperatures had significant negative correlation than rainfall in the study sites. Figure.29 shows yield variability in relation to climate variability of the two zones as shown by time series plots of Ngabu and Makhanga, Figure.29.

Regression analysis was done to determine the effect of each climate element on sorghum yield. In this comparison, influence of rainfall was more significant ($p<0.05$) to yield variability in the region. It was also shown that when all the climate elements were combined, their effect was most significant, (Figure.30). Individual climate elements poorly predicted the yield. This showed that influence of temperature alone using regression equation had little influence on the variability of sorghum yields.

Rainfall, maximum temperature and minimum temperatures' variances were explained by 41%, 7% and 9% respectively which showed superiority of rainfall influence on sorghum yields. When maximum and minimum temperature were combined, their effect accounted for 18% of variance while combination of all climate elements (rainfall, minimum and maximum temperatures and radiation), they explained 70% of the variance in the yield. The results also show that the most sensitive variable to sorghum production is rainfall, even though temperature changes exacerbated the effects through promotion of stomata closer and evapotranspiration. It was also shown that different climate elements had influence in the production of sorghum in the area.

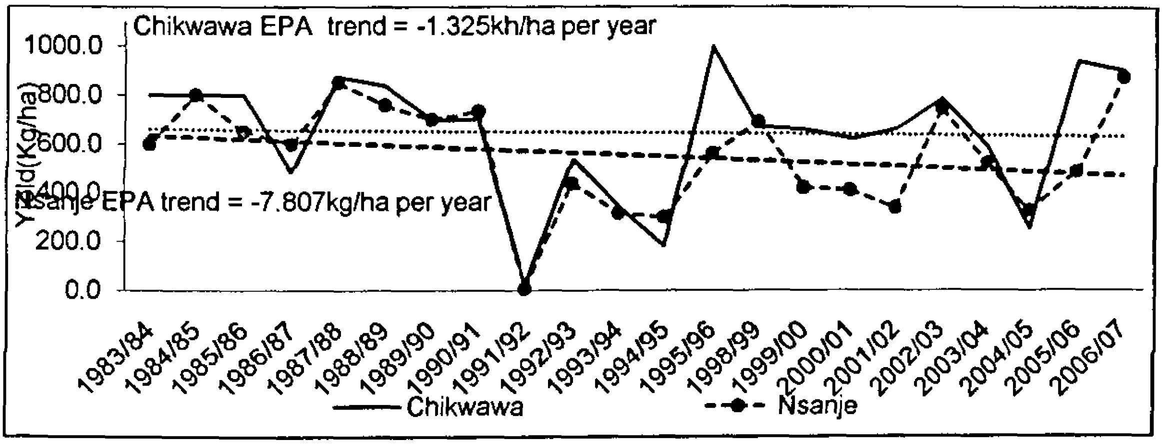


Figure 29 shows sorghum yield relationship for Chikwawa extension Planning Area (EPA) and Nsanje Extension Planning Area.

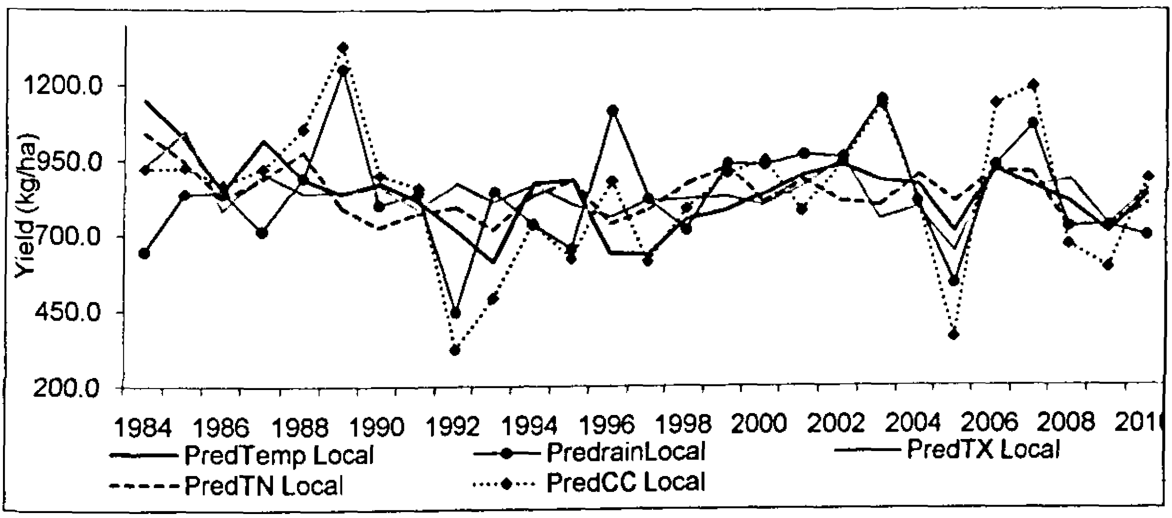


Figure 30 Shows comparison of the effects of climate variability to the potential sorghum yield (local variety).

Note Temp = min. and max. Temperatures, TX and TN are maximum and Minimum temperatures respectively, CC =combination of all climate variables.

4.4.2 Relationship between climate elements and Sorghum yield

First, correlation of seasonal rainfall between stations in the study sites was done and results showed a significant correlation at 95% level of significance as shown by Table.17 Monthly temperatures and Seasonal rainfall between stations were highly correlated indicated that the causal factors of these elements affect these stations nearly the same. Sorghum and climate variables were highly correlated at $p< 0.05$ significance level with a range of $r = -0.585$ to 0.563, $p<0.05$. The results as presented in Table.19. High correlation between climatic variables and sorghum yield suggested that there is big influence of climate variable on sorghum yield particularly during January to February (JFM) than October to December (OND). Rainfall showed a positive influence on sorghum yield which indicated that when there is reduction in rainfall, yield is reduced. However, from the study, the influence of OND rainfall is not significantly high, and over Ngabu and Makhanga, a negative relationship was observed. This negative relationship could be related to several factors that contribute to yield decline when sorghum is planted as early as October. Some of the reason could be excess moistures during maturing that lead to grain fungus and rotting, pests such as birds. Another explanation for the reason of lack of or poor correlation could be due to a shift in the season onset. In most years, shire valley experiences delayed onset or prolonged dry spells which forces farmers to plant late or replant. The results from correlation analysis also reflected the seasonal patterns of water availability to the crop via rainfall and eva-transpiration demand patterns. With reduced soil water availability at the beginning of the season, rainfall became more important which made late sowings advantageous. According to *Hammer, et al. (2011)* high temperature reduces sorghum yields and increases development rate, leaf number, leaf appearance rate and early flowering, He also observed significant reduction in plant height, pollen viability and seed set when temperatures are high. Apart from seasonal variability, yield decreased by 15.6kg/ha per year for fertilizer management practices of 25 and 50kg/ha. Without fertilizer application, decrease in yield was observed as shown by slope of the trend except for year 2098 where an increased of 3kg/ha per year was observed. The reason for this increase can be attributed to projected good rain season of this particular year.

Yield variability in the areas is mostly affected by pests and climate variability. Seasonal variation of the crop follows the rain pattern of the area. There was yield decrease in the year 1992 when the area experienced low rainfall due to drought. This signifies the importance of rainfall in influencing seasonal yield and production. Mean yield of the area for hybrid variety was 1191kg/ha and 784.5kg/ha for local variety, (Table.18). The standard deviation of the two varieties showed the variation of the crop yield in the area. As stated earlier, the most significant factor in the yield variability is weather and pests particularly birds. However, the existing differences between the two varieties are due to genetic difference of the two varieties and how they respond to climate variation. Table.18 shows statistical summary of yields in the Shire Valley.

Table 17 Correlation results of temperature for Ngabu and Makhanga and seasonal rainfall between stations

	NchaloSeas	NgabuSeas	MakhangaSeas	NgabuTmax	NgabuTmin
NgabuSeas	0.730				
MakhangaSeas	0.587	0.620			
ChikwawaSeas	0.750	0.590	0.412		
MakhangaTmax				0.757	0.234
MakhangaTmin				0.606	0.450

(Level of confidence =95%)

Table 18: Statistical summary of Observed Sorghum yield (n=26)

	Mean	SE.Mean	CI.mean.0.95	Variance	Std.dev	Coef.var
SVHYBRID	1191	89.7	185.6	19312.2	439.5	0.369
SVLOCAL	784.5	60.3	124.8	87389.2	295.6	0. 377

Table 19: Correlation of Seasonal rainfall (OND and JFM) with Sorghum Yield

Variable	SVRadn	NG OND	CK OND	NCH OND	MK OND	NG JFM	CK JFM	NCH JFM	MK JFM	NG OA	CK OA	MK OA	MKONDTX	MKJFMTX	NGONDTX	NGJFMTX
SVHYBRID	-0.4	-0.12	0.07	0.15	-0.22	0.44	0.54	0.49	0.12	0.27	0.5	0.01	-0.22	-0.5	-0.42	-0.55
SVLOCAL	-0.3	-0.04	0.12	0.19	-0.16	0.42	0.56	0.54	0.13	0.28	0.53	0.05	-0.19	-0.53	-0.41	-0.58

Note: Where Ng=Ngabu, MK=Makhanga, CK=Chikwawa and NCH=Nchalo

The results showed that temperatures minimum have a significant influence on sorghum yield than maximum temperature and solar radiation. Table.19 shows that during rainy season, JFM minimum temperatures are significantly related to sorghum yield (r = 0.508; 0.501, p-value = 0.05). The significant relationship is contributed by the processes of crop growth that requires temperature and radiation for photosynthesis, water uptake and other metabolism processes. Temperatures and rainfall are the largest influential elements in the optimal sorghum production in the area. Thus potential yield for sorghum increased (decreased) with increased (decreased) rainfall. Similarly decreased (increased) temperature increased (decreased) sorghum yields. This agrees with findings documented by *Hupet et al. (2000); Gong et al. (2006)* who indicated that minimum temperatures have a high effect on yield in dry season than during the rainy season since during rainy season there is little temperatures changes than in dry season.

Table 20: Correlation coefficients for Maximum Temperatures, Radiation and sorghum yield

Ngabu maximum temperatures					**Ngabu minimum temperatures**			
			Rainy season	Transition	Rainy season		Transition	
Variable	OND	JFM	AM	Radiation	OND	JFM	AM	OND
SVLOCAL	**-0.213**	**-0.3643**	**-0.3356**	**-0.3614**	**-0.331**	**-0.368**	**-0.365**	**-0.331**
SVHYBRID	**-0.201**	**-0.3417**	**-0.3624**	**-0.3168**	**-.3579**	**-0.3191**	**-0.3357**	**-.3579**

Table 21: Correlation coefficients for Rainfall with Sorghum yield

	Ngabu variables		Makhanga variables		Chikwawa variables			Nchalo variables		
Yields	JFM	OA	JFM	OA	OND	JFM	OA	OND	JFM	OA
SVLOCAL	0.502	0.369	0.254	0.132	0.163	0.638	0.607	0.223	0.64	0.627
SVHYBRID	0.518	0.355	0.221	0.126	0.155	0.627	0.577	0.231	0.604	0.585

Results of the correlation analysis between sorghum yield and total seasonal rainfall in the Shire Valley performed at 95% significant level. Note OA is total rainfall for October to March.

Correlated summary of sorghum yield in the Shire Valley and climate variable showed a negative relationship between temperatures for October- December (OND), January-February (JFM) and October-March (OA). Similarly radiation also showed similar results. The negative correlation of yield against radiation and temperatures showed that high temperatures would lead to reduction in yields. According to *(Vara Prasad et al., 2006)*, temperatures increase alters the photosynthetic mechanism of a sorghum crop by reducing its efficiency in the use of CO2, solar radiation, water and nitrogen. These changes would further lead to poor growth and hence decrease in the final yield. High temperatures also affect pollen viability of sorghum where cell turgidity the flower is reduced and in some cases die. This causes the crop to become infertile hence reduce grain per panicle.

Summary of correlated yields and climate variable (rainfall) in the area is given in Table.21. High correlation coefficients were found between JFM rainfall and sorghum yield as evidenced by the r values of 0.502, 0.638 and 0.627 for Nchalo, Chikwawa and Ngabu, respectively. This also showed that there is an increased potential for sorghum yield to decrease when rainfall is decreasing. Rainfall showed a high association with yield when correlated. The reason to this association is attributed to relationship rainfall has to other factors like temperature, humidity and water vapour. A decreasing trend in the rainfall had control mainly over cloud decrease and rains formation as a consequence of the global climate change. This in turn had increased air temperatures and number of dry days. Increase in temperatures had influenced in the increase of the rate of water vapour from the crop thereby decreasing the soil water content. This relationship shows how influential rainfall is in the sorghum production. Correlation of the CSIRO MK3 Model and observed monthly temperatures was also performed to identify level of association the two data sets. The results are presented by r in Table.22.

Similarly comparison of seasonal rainfall and sorghum yield was done graphically and the relationship showed sorghum response to climate variability. The relationship between variables and yield is an indication of climate influence on crop yield. The results of the correlation analysis shows that at vegetative stage, the total JFM rainfall significantly and positively correlated with sorghum yield at $p < 0.05$ significant level and the plot of raw data also affirms the observation, Figure.31.

Table.22	*CSIROtmax*	*Obsertmax*	*CSIROtmin*	*Observtmin*	*CSIROrain*
CSIROtmax	1				
Obsertmax	**0.838363**	1			
CSIROtmin	0.769303	0.751587	1		
Observtmin	0.550046	0.632561	**0.847266**	1	
Observrain	-0.08116	-0.04655	0.122501	0.165581	**0.39043**

Table.22 Relationship between observed and CSIRO Model temperatures correlated at 95% level of confidence rainfall.

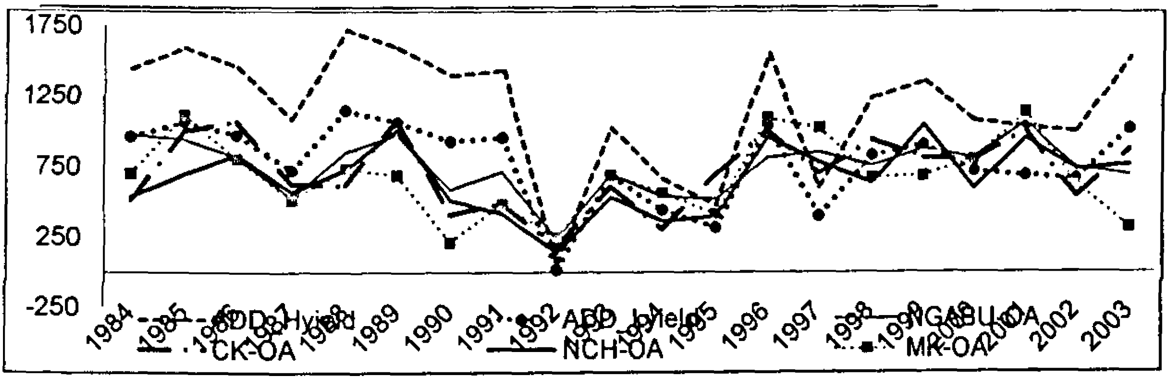


Figure 31 Observed Sorghum Yield and Seasonal Rainfall time series in the Shire Valley

4.4.3 Results from multiple regression models

A multiple regression model was developed to find the association of climate variables and sorghum yield. The joint significance of *Xj* and *Xk*, (where X*j* and X*k* are two different variables say, rainfall and temperatures) were fitted in a model with; and then without them in order to test the hypothesis whether variables can be excluded or excluded from the model.

Climate variables (rainfall, maximum and minimums temperatures) were used to predict the effect of climate variability on sorghum yield. Multiple regression analysis showed that seasonal total rainfall, radiation, minimum and maximum temperatures accounted for 51.3% ($P<0.03$) of the variation of local variety sorghum yield in the Shire Valley. According to *Adamu Ibrahim, et al, (2011)*, air temperature is the most important climatic element for good sorghum yield during the maturity stage. In this research, it was found that temperatures are significantly and negatively correlated with sorghum yield at 95% level. Analysis of the effect of rainfall on hybrid yield showed that 81.4% of the variation of hybrid yield ($p<0.0093$) was due to the combined influence of the climate variables (rainfall, radiation, temperatures).

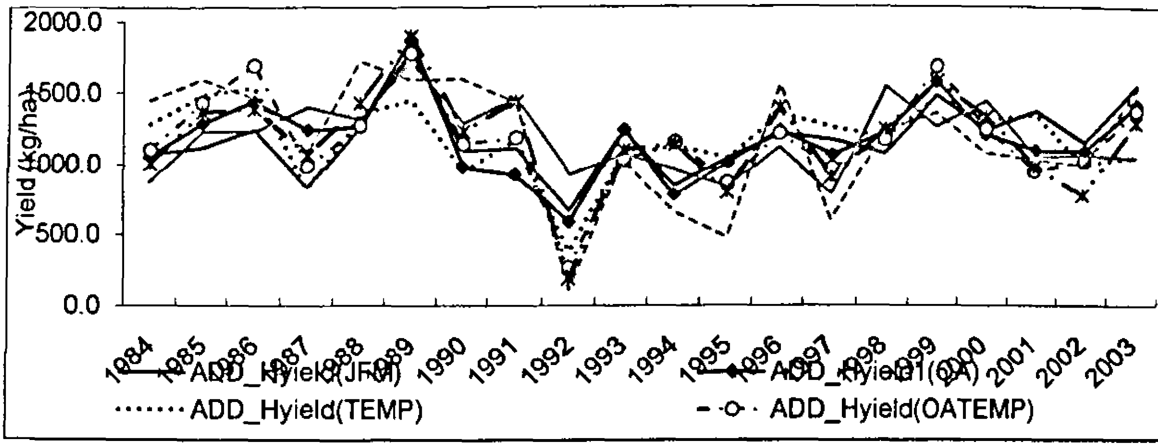


Figure 32 Comparison of the effect of climate variability on local sorghum yield in the Shire valley

The results further showed significant influence of rainfall and temperatures on the production of sorghum in the Shire Valley. Most stations showed increasing trend in temperatures while rainfall has decreased. Rapid increase in minimum temperatures magnitudes was noted in all the stations while Ngabu had an insignificant decreasing trend in maximum temperatures. As a result, hybrid yields also decreased with change in the climate variables as shown by Figure.32. Analysis of rainfall in all the study sites also revealed a decreasing trend in the long term time series (1960-2011).

Analysis of rainfall at Ngabu exposed an increasing trend for the period 1960-2011. Data set for Ngabu was divided into two sets at 1992 (i.e. 1960-1991 and 1992-2011), a decreasing trend was shown in the period (1992-2011) while 1960-1991 was showed an increasing trend which indicated influence of outliers in the data sets. Extreme events also showed a positive trend in warming (WSRI) and increasing in number of dry days (CDD). The overall contribution of climate variability in the area Figure.33 showed a decrease in the yield.

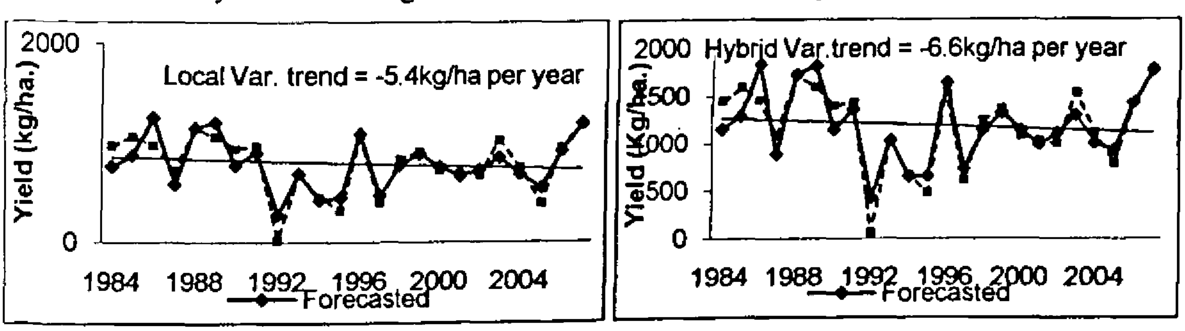


Figure 33 Shows comparison of observed and predicted sorghum yields for Local and Hybrid varieties in the Shire Valley

Statistical summary of the observed and the predicted sorghum yield are given in Table.23 below. The results showed a closer relationship of the observed and predicted values which indicated that rainfall and temperatures can be used to predicted yield in the Shire Valley.

Table 23: summary statistics of observed and simulated sorghum yield

Table 22	simulated_Local	Observed_Local	simulated_Hybrid	Observed_Hybrid
Mean	786.2324	786.2292	1188.943	1188.913
Standard Error	53.92495	60.14958	78.96863	87.49213
Median	762.3196	869.65	1149.118	1304.45
Standard Deviation	264.1772	294.6716	386.8657	428.6221
Sample Variance	69789.59	86831.33	149665.1	183716.9
Count	24	24	24	24
Conf/Level(95.0%)	111.5522	124.4289	163.359	180.9913

When individual variable was used to predict yields in the Shire Valley, the performance of the model became poor however, combined effects of all the seasonal variables improved the model performance as show by Figure.31 (a) and (b). The regression results have also shown that good relationship exist between sorghum yield (local and hybrid) and climate variables (temperatures, solar radiation and rainfall) such that a positive relation for temperature and radiation was obtained. The results further showed that estimation of yield in the Shire valley can better be explained by temperatures and rainfall other than radiation although radiation has an influence in the growth of the crop *(Escalada and Plucknett, 1975)*. When all the variables were combined to find their effects on yield, the model performance was much better than individual variable. This indicated that variability of sorghum yield in the area is not a contribution of a single climate factor. As such changes in the mean climatic conditions in the area exerted an influence by altering the viability of sorghum yield in some season.

4.4.4 Comparison of the influence of Scenario A2 and A1B on Shire Valley climate

The current (1961–2000) climate outputs from the CSIRO MK3 was first compared with observed means climatic data for Shire valley. However, it is unreasonable to expect that a large CSIROMK3 grid box (1.8°x1.8°) can represent climate for any particular point (ANL, 1994). Therefore, averages of observed and simulated monthly and seasonal air temperature and rainfall for Shire Valley were used. Two Scenarios A1B and B2 were compared and the results between the observed, A2 and A1B scenarios exhibited a wide gap.

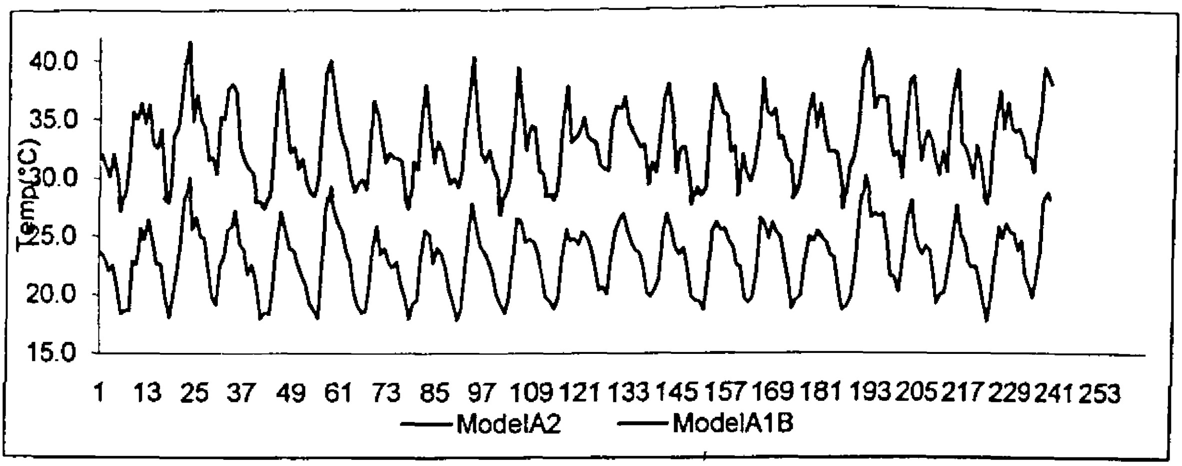


Figure 34 Comparison of monthly mean temperatures for SRESA2 and SRESA1B

The difference occurred due to difference in the assumption considered when projecting the temperature data in the two scenarios. Scenario A1B raw data closely explain the observed, although in all scenarios, inter-annual variations are well captured (Figure.34 and 35.)

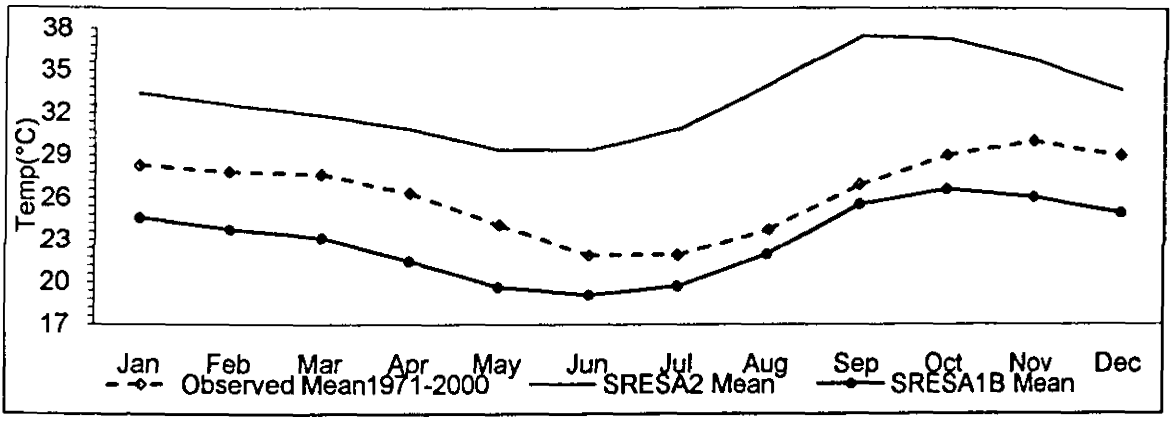


Figure 35 Comparison of Scenarios A2 and A1B 30 year mean temperature against observed data from Ngabu

A plot of scenarios A1B and A2 time series Figure.34 shows seasonality of temperatures pattern of the model which corresponds to the observed records within the stations. Correlation between simulated temperature for scenario SRESA2 and SRESA1B showed a significant association of the two sets with r=0.73 at 95% significance level. Considering a temperature rise by 2100, the analysis of scenarios showed that scenario A2 is the "hottest" scenario followed by scenario A1B. However, in scenario A1B, the assumption is that fossil CO2 emissions are expected to be falling by 2100, while a continual rise is expected in scenario A2 (http//www.climate.unibe.ch/jcm/doc/emit/sres.html).

Scenario A2 also has relatively higher sulphate emissions than A1FI (this cause local cooling). In scenario B1, the emissions of methane and HFCs are also much lower. As shown by Figure.35, the monthly temperatures for A2 are higher in all months than for scenario A1B.

Despite the difference in the magnitude of their forecast, the two scenarios have shown similar pattern of months to month variability although A2 showed more variation in temperatures than scenario A1B as contributed by the assumption factors.

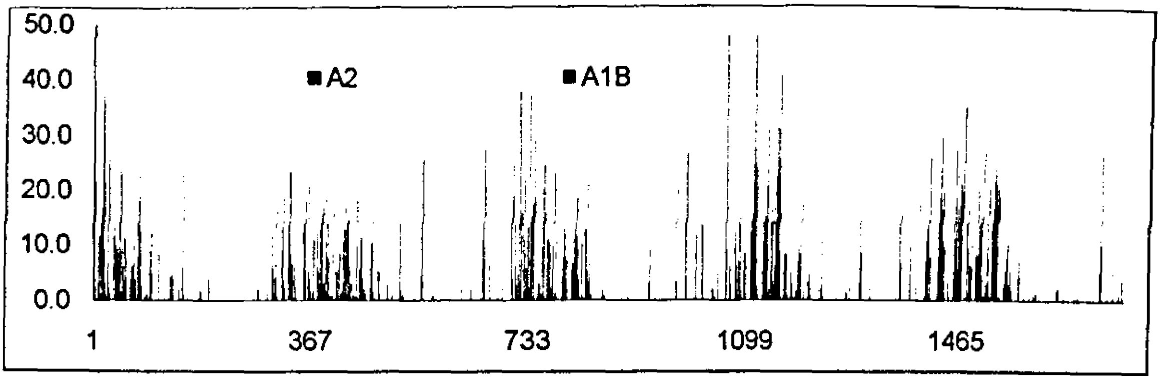


Figure 36 Comparison of CSIRO Daily rainfall for scenario A2 and A1B (2001-2030)

4.5 Comparison of Temperatures for SRESA2 and SRESA1B

Table 24 Mean Temperature of Scenario A2 and A1B

Scenarios	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
SRESA2 Mean (2046-65)	33.4	32.6	31.9	30.9	29.5	29.4	30.9	34.1	37.5	37.3	35.9	34
SRESA1B Mean (2046-65)	24.6	23.8	23.2	21.5	19.7	19.1	19.7	22	25.6	26.6	26.1	25

From the Table.24 above, it is shown that temperatures for scenario A2 differ from A1B by a wider margin, ~10°C. A correction factors was performed on the data sets, SREA1B was closely related to observed data than scenario A2.

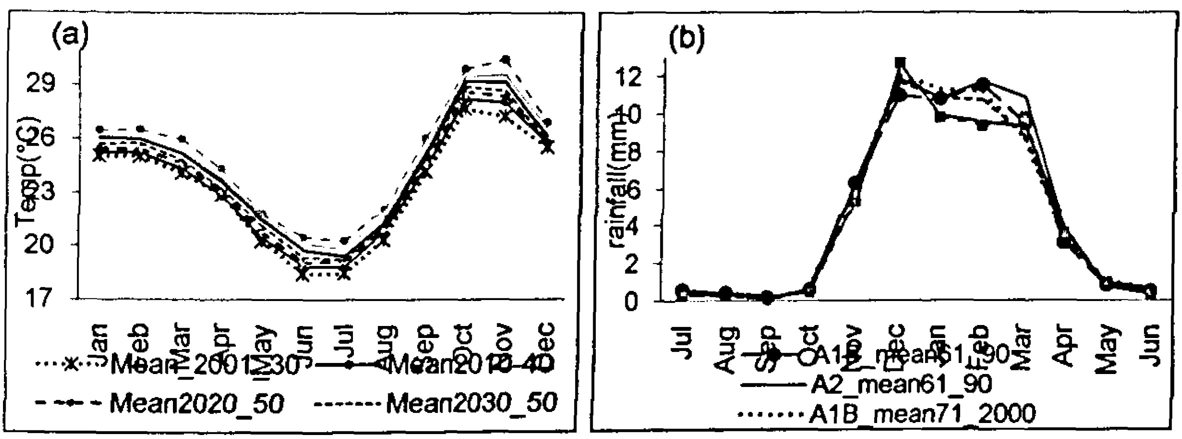


Figure 37 Comparison of SRESA2 and SRESA1B long term mean temperatures and rainfall at Ngabu.

4.4.6 Rainfall variability of scenario A2 and A1B Mean rainfall

Fig 39 show plots of monthly temperatures for November and October, and mean annual rainfall for Ngabu. November temperatures showed increased variability than October. Increased trend was shown by the plots which indicated the degree of the impact of future climate extremes in the Shire Valley. *McNider et al.,(2009)* suggested increase in green house gases (aerosols) and increase in atmospheric moisture as the cause of the increase in future temperatures. A decrease in mean annual rainfall was shown between 2012-2100 over Ngabu as shown by Figure.39 while temperature plot showed an increase in the trend with November increasing more than October.

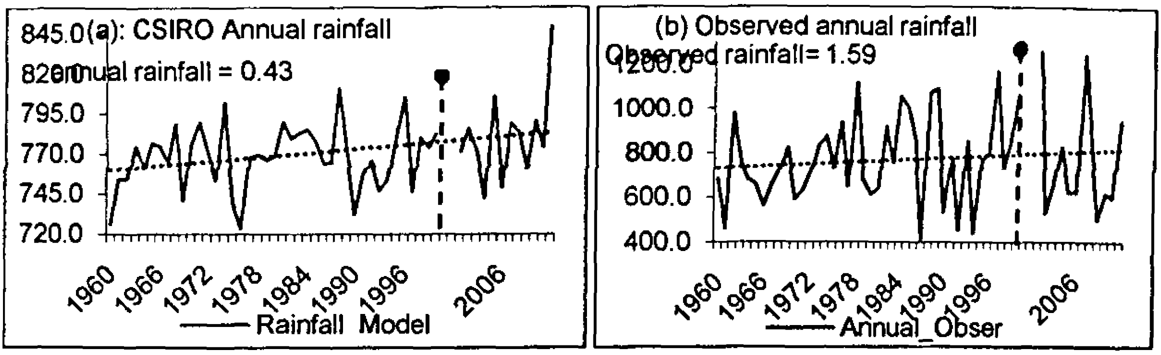
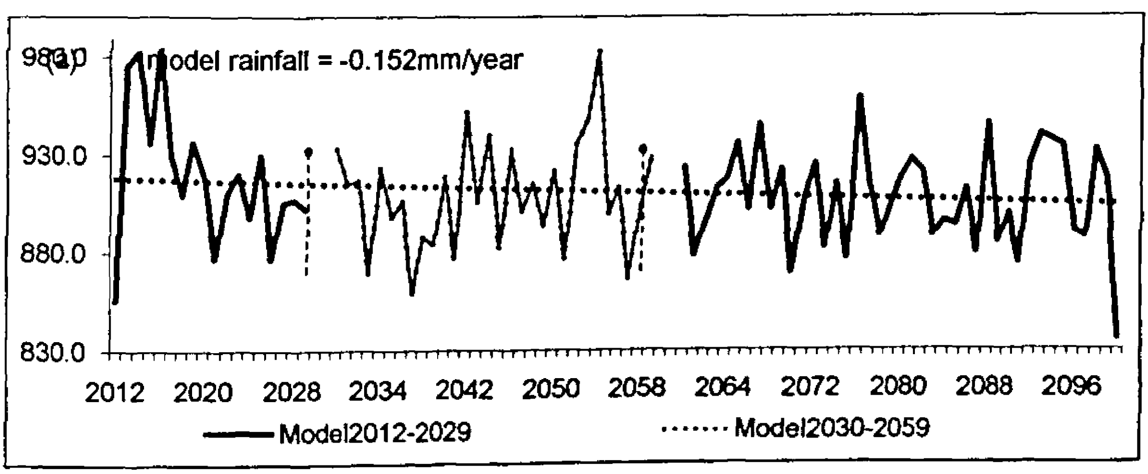


Figure.38: Present annual rainfall from (a) CSIRO Model and (b) Observed Ngabu rainfall

Table 25: Statistical summary of present and future temperatures in the Shire Valley

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Mean2001-2030	*25.0*	*25.0*	*24.1*	*22.9*	*20.3*	*18.4*	*18.5*	*20.3*	*24.2*	*27.7*	*27.3*	*25.5*
Std. Deviation	*0.69*	*0.55*	*0.59*	*0.67*	*1.03*	*1.15*	*1.14*	*1.12*	*0.93*	*0.96*	*1.95*	*0.89*
Sample Variance	***0.47***	***0.30***	***0.34***	***0.45***	***1.06***	***1.33***	***1.31***	***1.26***	***0.86***	***0.92***	***3.80***	***0.79***
Mean2031-2060	*25.7*	*25.7*	*24.8*	*23.3*	*21.1*	*19.4*	*19.2*	*21.2*	*25.0*	*28.9*	*28.8*	*25.8*
Std. Deviation	*0.80*	*0.81*	*0.72*	*0.81*	*1.04*	*1.08*	*0.95*	*1.05*	*1.08*	*0.83*	*1.52*	*0.90*
Sample Variance	***0.64***	***0.65***	***0.52***	***0.65***	***1.07***	***1.16***	***0.90***	***1.10***	***1.17***	***0.70***	***2.32***	***0.81***
Mean2061-2090	*26.5*	*26.5*	*25.9*	*24.3*	*21.9*	*20.5*	*20.3*	*22.1*	*26.0*	*29.9*	*30.4*	*26.9*
Standard Error	*0.1*	*0.1*	*0.1*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	*0.4*	*0.2*
Std. Deviation	*0.6*	*0.6*	*0.7*	*1.0*	*1.1*	*1.2*	*1.1*	*1.2*	*1.1*	*1.0*	*2.0*	*1.3*
Sample Variance	***0.4***	***0.4***	***0.5***	***1.0***	***1.1***	***1.3***	***1.2***	***1.4***	***1.2***	***1.0***	***4.0***	***1.8***
Observed Mean1971-2000	**28.3**	**27.9**	**27.7**	**26.4**	**24.1**	**21.9**	**22**	**23.8**	**27**	**29.1**	**30.1**	**29**



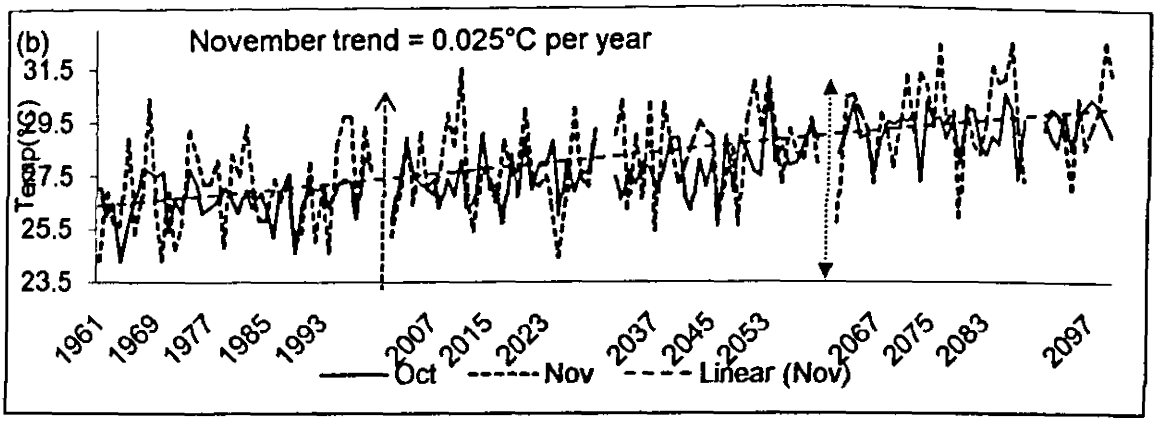


Figure 39: shows (a) future rainfall trend of CSIRO Model and (b) comparison of CSIRO monthly mean temperatures for October and November at Ngabu

4.4.7 Projection of future climate variability

Rainfall and temperatures from the models were related by applying regression equations and the output compared with the observed. Regression analysis was used to correct the data series so as to resemble the observed data. The reason for this was to add magnitude to the data so that it can easily be related to the observed data sets. Table.26 below gives the regression models used in mapping climate variables. Radiation was not mapped on the assumption that its future change will be small. From results, it can be seen that regardless of the significance of the results, rainfall was poorly mapped with R^2=0.152, p-value < 2.0e-16.

Table 26 Regression model used for mapping climate variable

Tmax_fsct(°C)	=9.00401+0.82072*CSIROtmax. Multiple R-squared 0.703, R-squared 0.703, F-statistic 1.38e+04, p-value <2.0e-16
Tmin_fsct (°C)	=0.94777+0.92721*CSIROtmin. Multiple R-squared 0.718, R-squared 0.718, F-statistic 1.49e+04, p-value <2.0e-16
Rainfall fcst(mm)	Rain_Fsct=0.07755+0.5779*CSIROrain. Multiple R-squared 0.152, R-squared 0.152, F-statistic 1.05e+03, p-value <2.0e-16

4.4.8 Comparison of CSIRO Model Output and Observed Shire Valley daily

A comparison of Observed and CSIRO Model rainfall and temperature (maximum and minimum) at Ngabu Station was done and the results showed that the model data fall short of the observed records (Figures.40 and 41). Temperatures showed a minor difference to the observed temperatures of the areas while rainfall showed wider difference although on daily average it was almost similar. From summaries of statistics, it was observed that there is a relationship between model output and the observed rainfall, Figure.38 and 39.

When the observed data set was compared with the mapped model data set, the results from the model were overestimating the variability of rainfall in the area as noted by the difference in COV of the observed and mapped model data. The reason for this could be attributed to the model physics and resolution, CSIRO Mk3 has a spatial resolution of 1.8°x1.8° which is approximately 200 sq. Kilometres and with this resolution local scale factors that contribute to rainfall may not be captured.

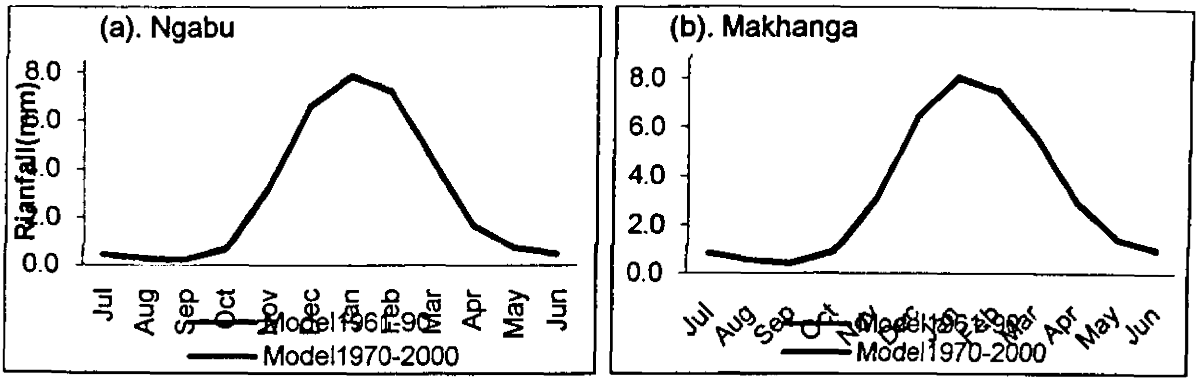


Figure 40 Comparison of CSIRO Output and Observed rainfall for Ngabu and Makhanga

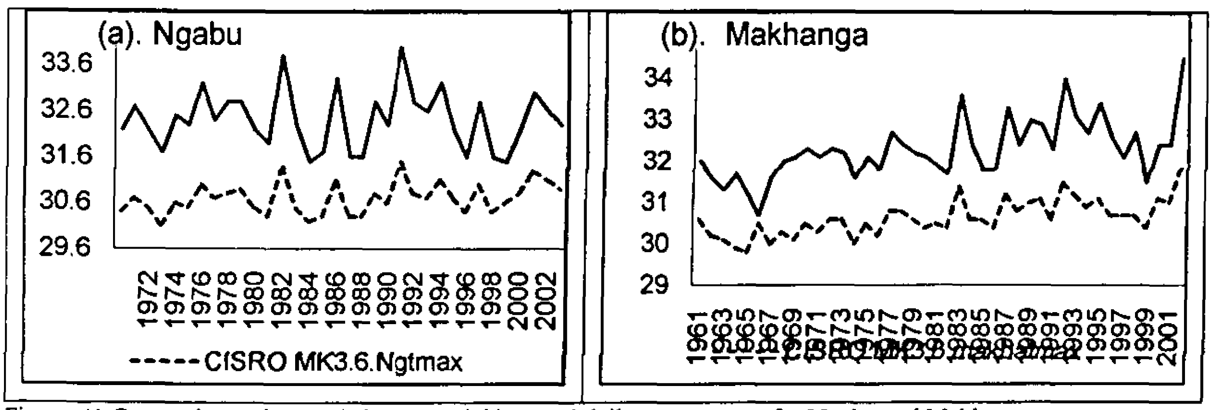


Figure 41 Comparison of CSIRO Output and Observed daily temperature for Ngabu and Makhanga.

Table 27 Seasonal mean temperatures for Shire Valley

Period	JFM	OND
1971-2000	26.7	29.5
2001-2030	27.8	30.9
2031-2060	29.0	31.3
2061-2100	30.3	33.3

In Table 27, variability in future mean temperatures showed an increase in the mean temperature over the region. JFM temperatures increased by 4% during 2001-2030 and by 9% from 2031-2060 but reached 13% by 2100. OND temperatures increased from 5% to 13% in the same period. Long term CSIRO Model output mean for Makhanga and Ngabu were also analyzed. The peak month of rainfall is January in all the station although different peak months were observed in the model as shown in Figure.41. The results showed a general agreement with observed data except for the model failure to capture month to month variability as shown by the uniform increase. Correlation of these data sets at 95% level of confidence showed significant relationship between the data sets. Maximum and minimum temperatures were significantly related, r=0.838 and r=0.752 respectively and rainfall had r=0.390. With this relationship between variables, linear regression equations were developed for each model output in relation to the observed data. The equations developed were then used to map future data sets for use in the APSIM Model.

4.4.9 Model versus Observed

Comparison of raw model output and the observed data showed that model outputs can be used to relate yield to the climate variability on monthly time scale (some of the results can be found in the appendix). Analysis of the CSIRO MK3.6 Model output was done to relate how the models presented climate variability over Shire Valley area. Temperature and rainfall from 1960-2000 were used to compare with the observed data records while 2001-2100 model output data was used to project the future. Figure.42 shows an increase in mean monthly temperatures for 2001-2090. The months of March to May showed decrease in the future mean temperatures while summer temperatures increased rapidly particularly between October and February and this was corresponding to findings which showed increase in the mean temperature for JFM by 4% during 2001-2030 and increased by 9% from 2031-2060 but reached 13% by 2100. The results showed a general agreement with observed data except for the model failure to capture month to month variability as shown by the uniform increase. In comparison to observed data set, winter warming was shown by increase in June and July temperatures for all the time period.

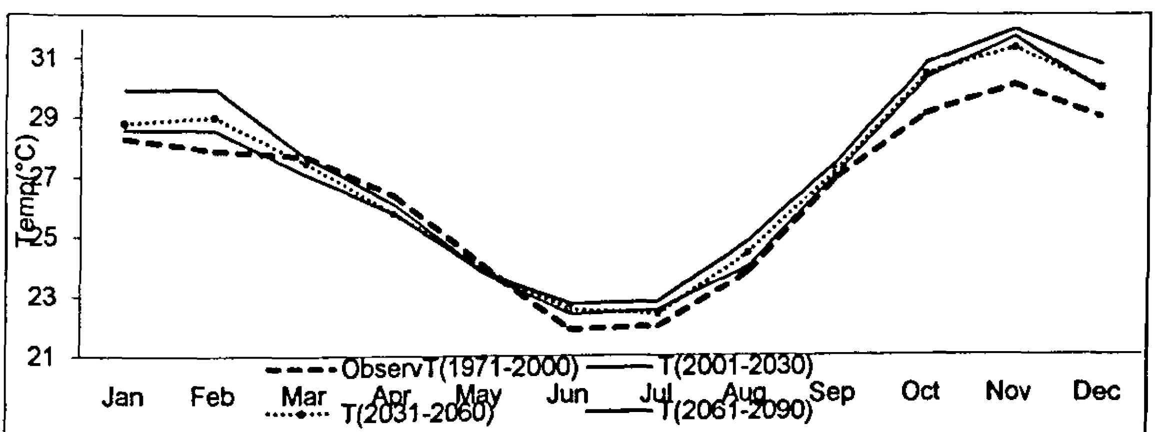


Figure 42 Comparison of CSIRO Model Output and Observed monthly temperature for Ngabu in the Shire Valley

The relationship between the model and Observed June and November was also represented graphically as shown in Figure.44 while Figure.43 shows daily variation of model data. The months November October and December and May, June and July were selected to represent lowest temperatures (in winter) and highest (in summer) temperatures in a year.

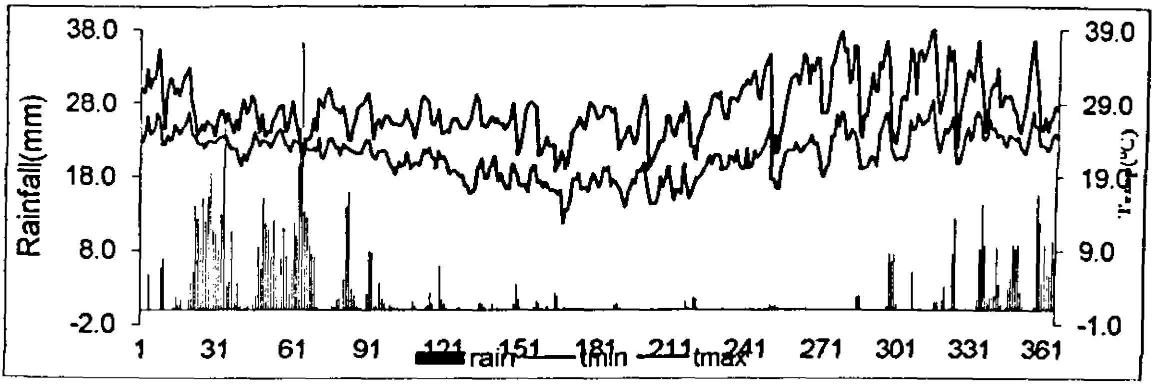


Figure 43 show variability in the daily maximum and minimum temperatures and rainfall for 1984 at Ngabu meteorological station.

The models temperatures for these months were then compared to the observed temperatures of similar months with an aim of relating the model and observed performance in depicting rate of temperature change. Ngabu temperatures were warmer than Makhanga with a difference of 2°C in minimum temperatures and about 0.5°C in maximum temperatures as shown in Table.28.

Table 28 Statistical summary for Temperature over Ngabu and Makhanga

Variable	Mean	StDev	Median	MAD	Std.Error
MakhangaTmax	33.88	0.89	33.9	0.74	0.16
NgabuTmax	34.02	0.74	33.9	0.44	0.13
MakhangaTmin	22.80	0.53	22.8	0.44	0.09
NgabuTmin	26.96	1.22	27.1	1.04	0.22

Statistical summary of Observed minimum and maximum temperatures from Ngabu and Makhanga Stations.

In order to correctly simulate the future yield trends, the discrepancies in the data need to be corrected. And correction was done through application of a correction factor to the model output. This was achieved through application of correlation and regression analysis. The mapped data set was then used to simulate future sorghum yield in APSIM Model. This was done through us of simple regression analysis. Figure.44 shows monthly temperature variability for the month of May, June and July. The month of June showed increasing trend ($p < 0.05$) significance more than May and July which agrees with observed data which also revealed that May to August is warming faster than summer temperatures *OND* and *JFM* even though *OND* temperatures were the highest among all the other. The difference in these temperatures was a result of decreased in daily variability of temperature in winter and increased variability during summer (Table.2b and 3c). This also affirmed findings by *Meelh et al., (2000)* who showed that increases in the daily minimum temperature values over land areas are larger than those of daily maximum temperature. He also found that in many regions nighttime low temperatures has increased more than daytime highs, thus reducing the diurnal temperature range. Increase in winter monthly temperatures was shown by both the model output as well as the observed temperature records. A similar situation was also observed in mean monthly temperature for summer season (October, November and December, Figure.39). A general increased trend was observed for the month of November which showed higher temperatures than any other months; trend of its increase was 0.052°C/year.

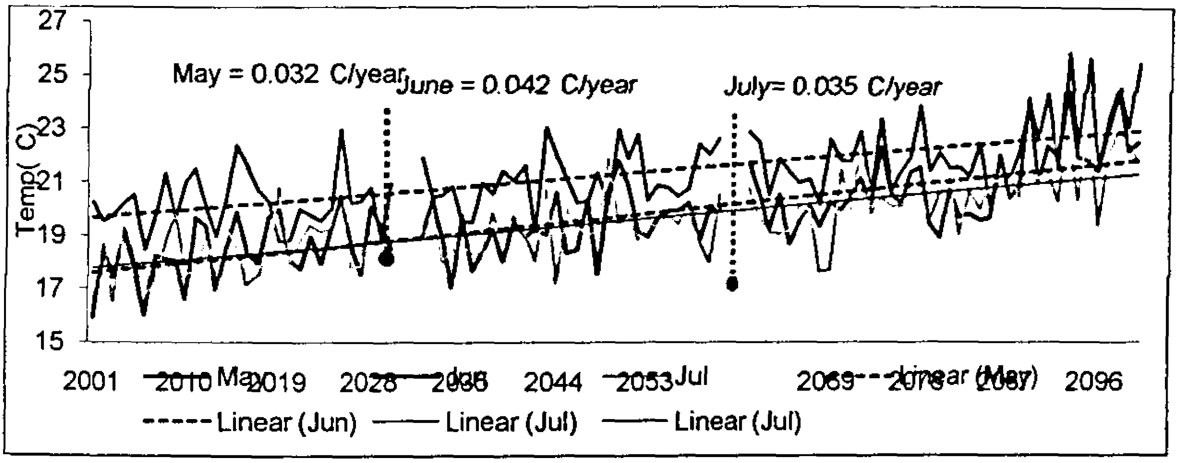


Figure 44 Variability of future monthly temperature at Ngabu

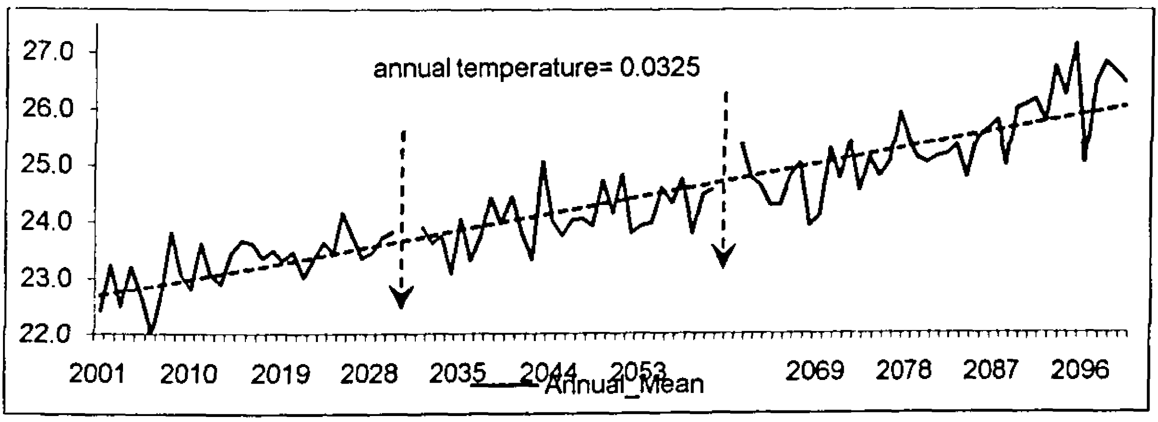


Figure 45 Future annual mean temperatures for Ngabu

Figure.46 and Figure.47 shows trend in temperature for present and in the future. It was observed that future minimum temperatures would increase by 4.0°C between 2001- 2100 which agrees with the IPCC future climate projections, *(IPCC, 2007)*. At a crude model resolution of 1.8°, comparison of observed and model temperatures output for November showed a small difference indicating ability of CSIRO MK3 model in capturing variability of climate elements in the study areas. Comparison of the observed and Model output also depicted the same increasing trend for future temperature as shown by Figures 46 and 47.

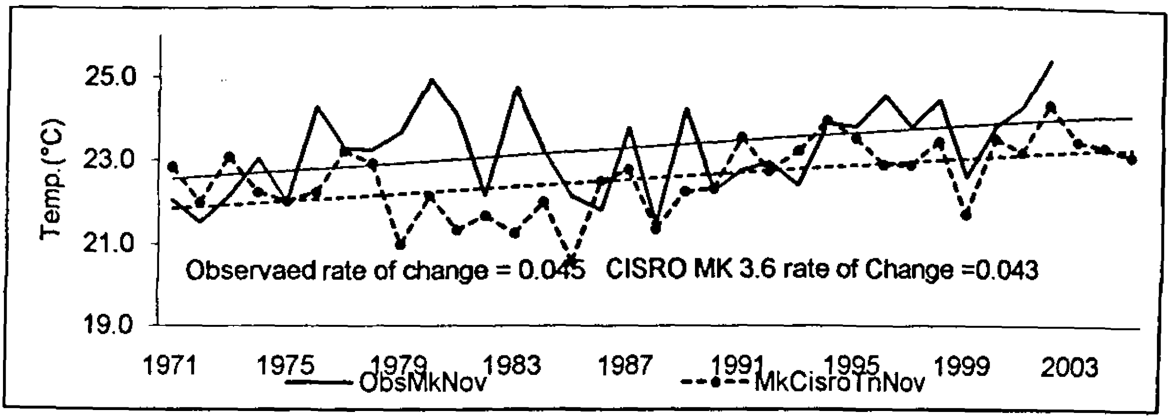


Figure 46 Comparison of CSIRO MK3.6 and Observed November Minimum Temperatures for Makhanga

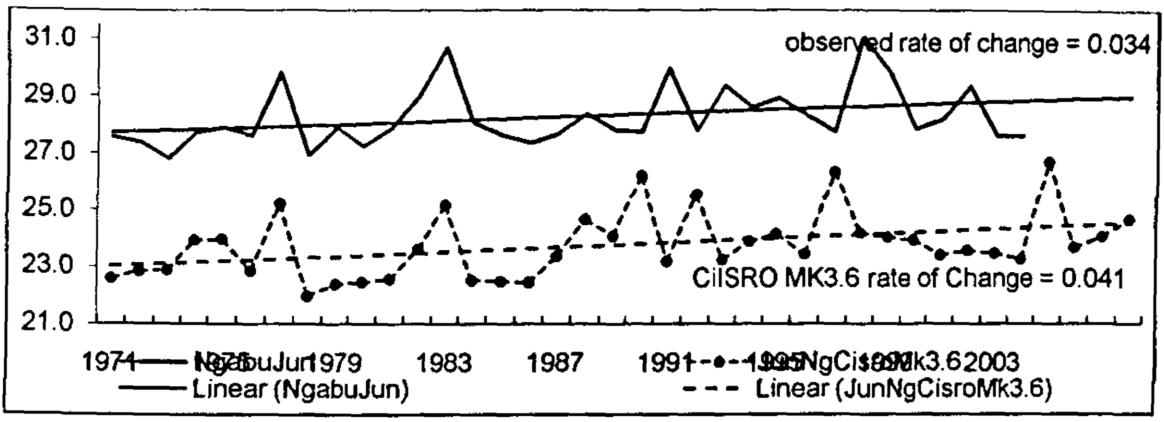


Figure 47 Comparison of Observed and CISRO MK3.6 for June Maximum temperatures for Ngabu Station

Mean rainfall for 1961-2000

To find out the relationship between future climate scenarios and sorghum yield, models statistics were performed on the climate variable outputs from the GCM CSIRO MK 3.6 Model. The results showed that most stations had insignificant positive trend in both minimum and maximum temperatures. Minimum temperatures showed a rapid increase than maximum temperatures. The cause for night time warming in the observed temperatures has been attributed to stability, increases in atmospheric water vapor and changes in greenhouse gas forcing, surface roughness, cloudiness, and surface heat capacity and warming in the nocturnal boundary layer due to a redistribution of heat *(McNider, et al., 2009)*. Earlier results pertaining to changes of temperature extremes was that higher mean temperatures increase the probability of extreme warm days and decrease the probability of extreme cold days *(Meehl, et al., 2010)*. Seasonal rainfall analysis (Table.29) also revealed evidence of increased intensity of daily rainfall, manifested through increased frequency of wet days and an increased proportion of total rainfall during heavy events.

Table 29 summary of mapped monthly rainfall for CSIRO Model

1961-2000	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Mean	***230.3***	***177.9***	***132.8***	***44.4***	***18.9***	***15.6***	***16.4***	***6.29***	***5.03***	***20.96***	***72.2***	***219.2***
Standard Error	0.59	2.612	0.065	0.23	0.33	0.09	0.39	0.06	0.05	0.002	0.37	1.728
Median	230	181.3	132.9	44.1	18.8	15.8	15.4	6.39	5.16	20.96	72.6	217.2
Standard Deviation	3.73	16.52	0.413	1.48	2.08	0.57	2.44	0.41	0.31	0.015	2.33	10.93
Sample Variance	**13.91**	**272.9**	**0.171**	**2.19**	**4.33**	**0.32**	**5.97**	**0.17**	**0.1**	**2E-04**	**5.45**	**119.5**
Conf. Level(95.0%)	1.193	5.284	0.132	0.47	0.67	0.18	0.78	0.13	0.1	0.005	0.75	3.495

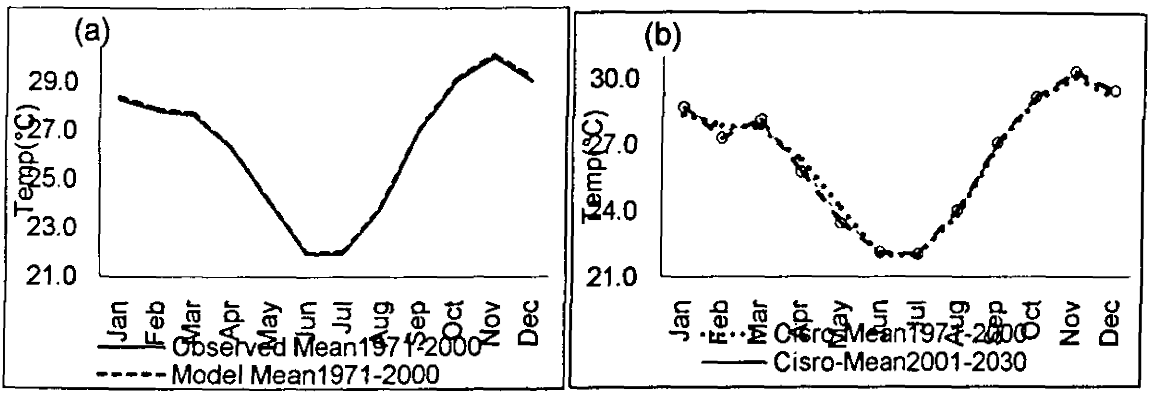


Figure 48 shows the relationship between of (a) Observed monthly temperature (Ngabu) and CSIRO mapped temperature; (b) Ngabu long term means monthly temperatures from CSIRO Model.

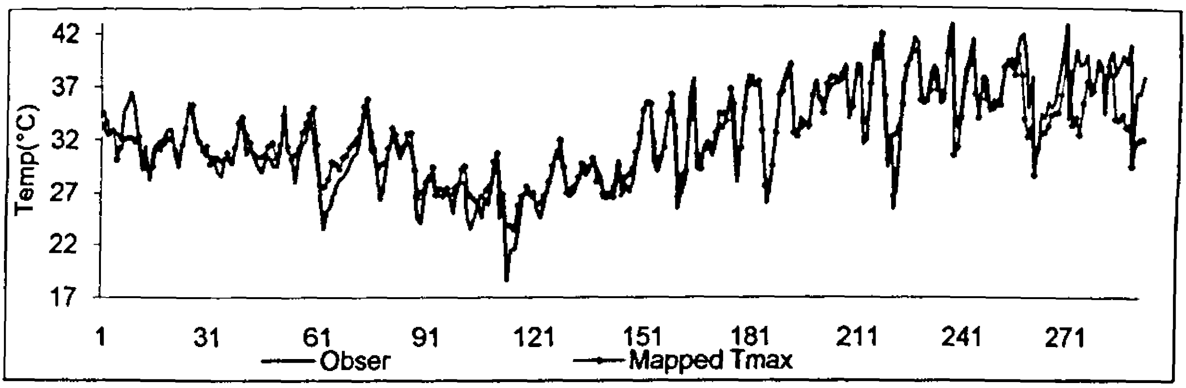
Table 30 Correlation of Ngabu Observed temperatures and CSIRO Mk3.6 Model out put

	NgabuJunTmin	*JunNgCSIROMk3.6*	*NgabuNovtmin*	*NovNgCSIROMk3.6*	*NgabuNovTmax*	*NovNgCSIROMk3.6*	*NgabuJuntmax*
JunNgCSIRO Mk3.6	**0.630**	1					
NovNgCSIRO Mk3.6	0.241	0.2615	**0.698**	1			
NgabuNov Tmax	0.012	-0.132	**0.843**	0.583	1		
NovNgCSIRO Mk3.6	0.108	0.112	**0.638**	**0.707**	**0.703**	1	
JunNgCSIRO Mk3.6	**0.552**	**0.445**	0.065	0.234	0.092	**0.374**	**0.354**

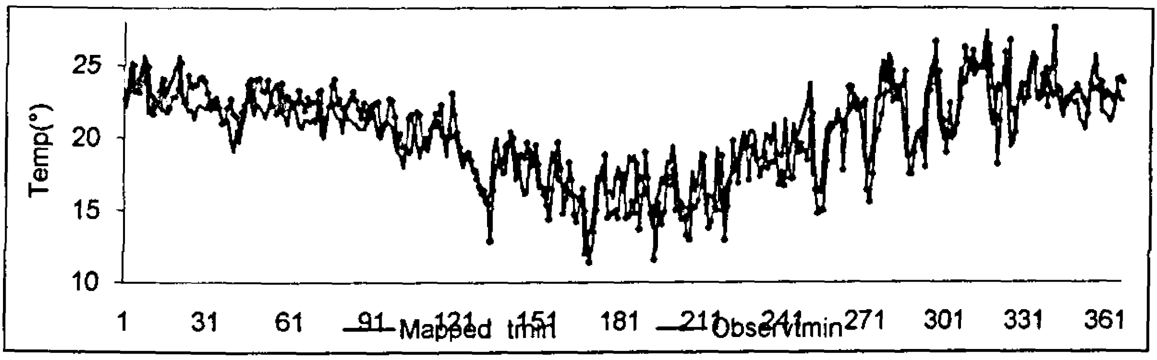
4.5 Regression Models

The interaction between climate model CSIRO MK3 Model output and observed variables in the Shire Valley predicted the climate variable accurately except for rainfall (Figure.48). Model rainfall pattern for the area showed increased variability although it was different in amount to the observed. The reason for this shortfall is probably due to the difficulties encountered in modelling clouds physics of the GCM model. Linear regression analysis was performed to find the interaction between the observed and the model output climate elements. The interaction involved factors that influence climate in the Shire Valley and global circulations model factors. Ngabu daily rainfall and temperatures were subjected to the analysis in order to map the model output data sets to the observed. Figure.49 shows the relationship of the observed data set and the corrected model output data sets for (a) & (b) temperatures and (c) rainfall.

(a) Ngabu Maximum Temperatures (°C)



b. Ngabu Maximum Temperatures (°C)



c. Ngabu daily rainfall (mm)

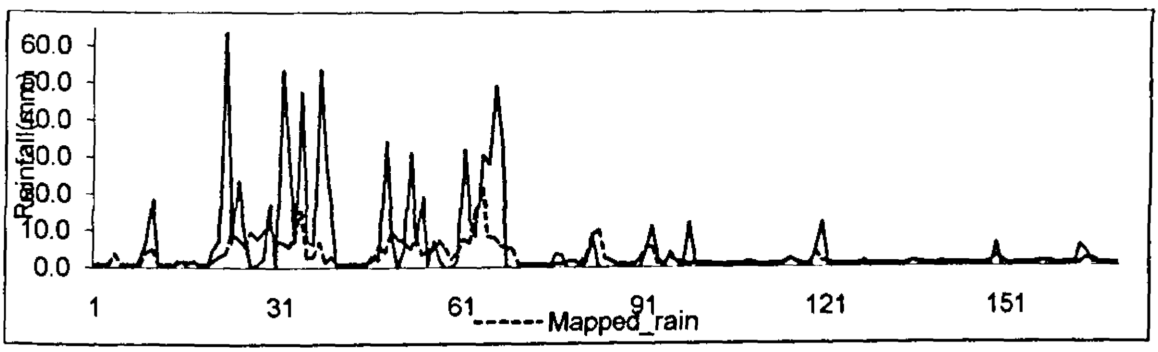


Figure 49 Comparison of CSIRO model mapped and observed (a) daily maximum temperature, (b) daily minimum temperatures and (c) daily rainfall at Ngabu Met. Station

The predicted and observed daily data was plotted to compare their variability, Figure.49 (a&b). For correction of the data the regression equation 1-5 in the appendix were developed. It was clear from the results that temperature from the CSIRO model output significantly *(P<0.005)* explained the variance in the observed rainfall and temperatures data. The regression equations (1) & (3) explained >70% of the variance in the temperatures of the region. However, in equation 3, rainfall was poorly related to the model output as seen by the 15% explanations of the variance. The reason for this could be the challenges scientists have in modelling clouds physics and related parameters.

In equation 4 and 5 in the appendix, it was observed that CSIRO model significantly predicted maximum and minimum annual temperatures for Ngabu, β =1.67, t(32)=11.88, p<0.001. CSIRO Model maximum annual temperatures also explained a significant proportion of variance in maximum temperatures by 82%, F(0.05, 32) = 141.1, p<0.001. Predicting equation for maximum annual temperatures at Makhanga was given by β= -.34, $t(41)$ = 12.31, p <0.001. CSIRO maximum annual temperatures also explained a significant proportion of variance in maximum annual temperatures for Makhanga by 79%, $F(1, 41)$ = 151.50, p < .001. As the p-value was much less than 0.05, the null hypothesis that β = 0 was rejected justifying the significance of relationship as explained by the variance in over Makhanga. The regression model predicted temperatures were plotted together with the observed Figure.50 and the results showed that the model explained ~80% of rainfall variability pattern of the areas.

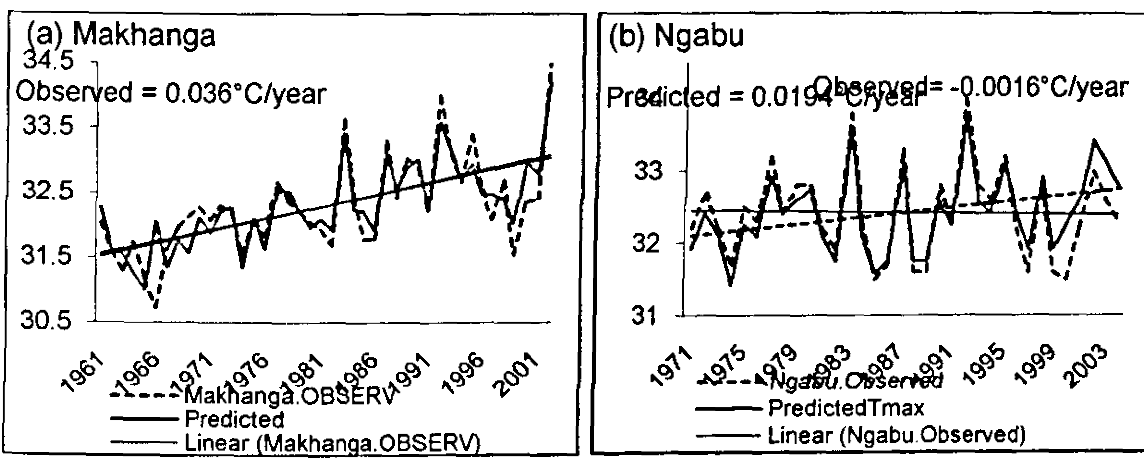


Figure 50 Comparison of observed and predicted annual maximum temperatures from (a) Makhanga and (b) Ngabu

The developed models used to correct temperatures are given by equations 4 and 5. To determine usefulness of predicted data, monthly data sets were also analysed. Figure.51 (a-b) and Figure.52 (a-b) shows comparison between the predicted model and observed data at Ngabu and Makhanga.

The linear regression line for rainfall was poorly related to the observed rainfall over the study sites as it approximate only 15% of variation (p<2.0e-16) at 95% significance level as explained by CSIRO Model out rainfall. This is in agreement to the finding of most climate change scientist who showed that the GCM model poorly simulates rainfall *(McSweeney, 2008)*.

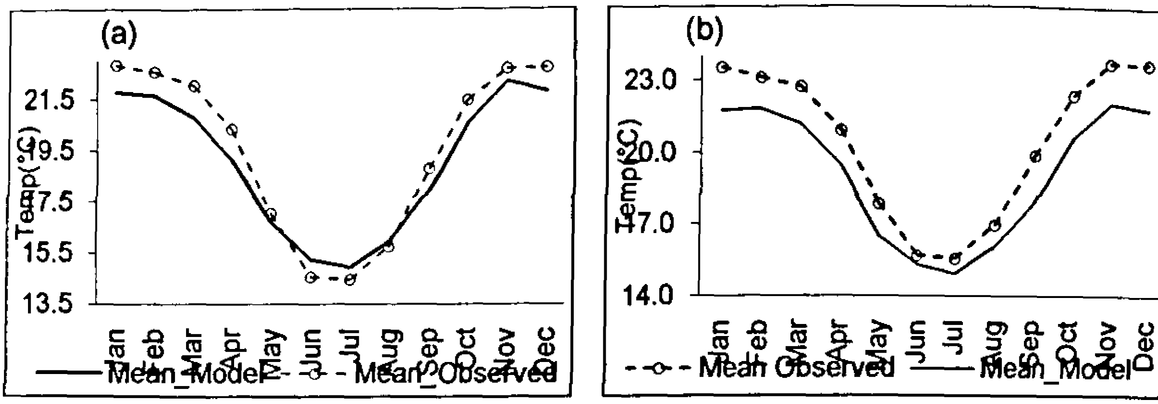


Figure 51 Comparison of observed and predicted long term mean minimum temperatures from Makhanga and Ngabu (1971-2000)

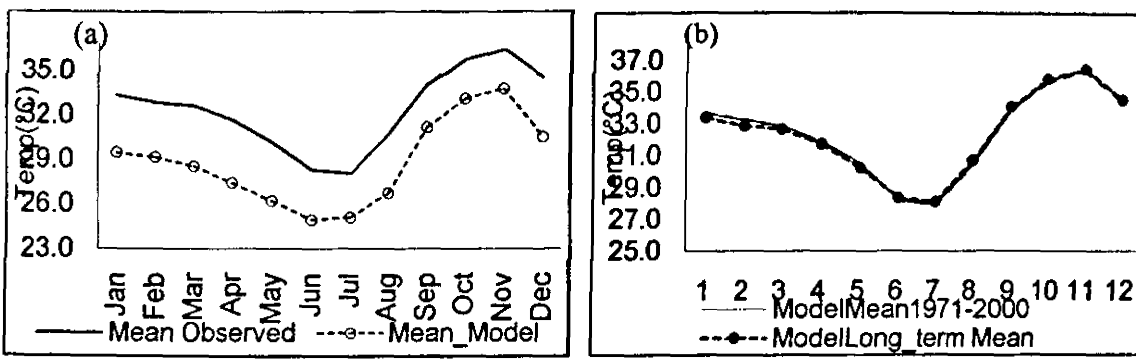


Figure 52 Shows comparison of long term means for (a) observed and Model maximum temperature (raw data) and (b) projected long term mean temperature for Ngabu station for January to December.

Comparison of observed time series with the model long term mean for minimum temperatures show warming in winter season (May to August) at Makhanga. However Ngabu temperatures showed that observed minimum temperatures were warmer than the model. This indicates that geographical features, location and other factors contribute to the differences in the warming. The other reason could be attributed to spatial resolution (1.8°x1.8°) of the model which does not include small scale features that have influence on the temperatures changes. Figure.51 shows the yield obtained by simulating using Model climate variables outputs and observed yield with 1°C increase in both maximum and minimum temperatures and 5% decrease in rainfall. The regression statistics are shown below Figure.53. Climate variables (rainfall, maximum and minimums temperatures) significantly explained variability of sorghum yields in both hybrid and local varieties for the Shire Valley, (β = -.34, $t(41)$ = 12.31, p < .001). The variables also explained a significant proportion of variance in maximum annual temperatures for hybrid variety scores, R^2 = 0.81, $F(1, 13)$ = 3.38, p < 0.03 and for local variety, R^2 = 0.80, $F(1, 13)$ = 3.15, p < 0.03.

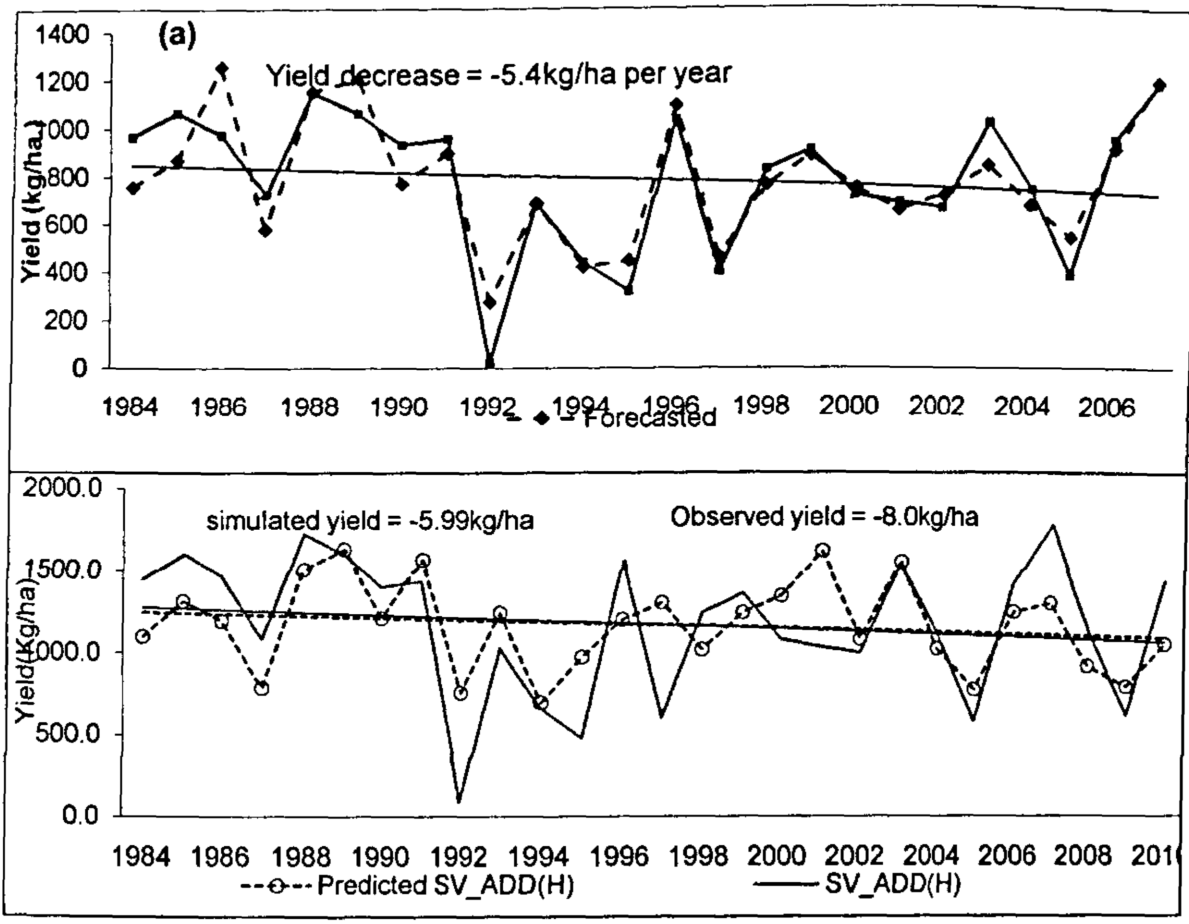


Figure.53 Shows comparison of predicated and observed yields from regression equation for (a) local and (b) hybrid varieties in the Shire Valley. (Multiple R = 0.569, R Square = 0.399, Adjusted R Square = 0.290, Standard Error = 364.74, F stats= 3.657, *P-value* = 0.0198)

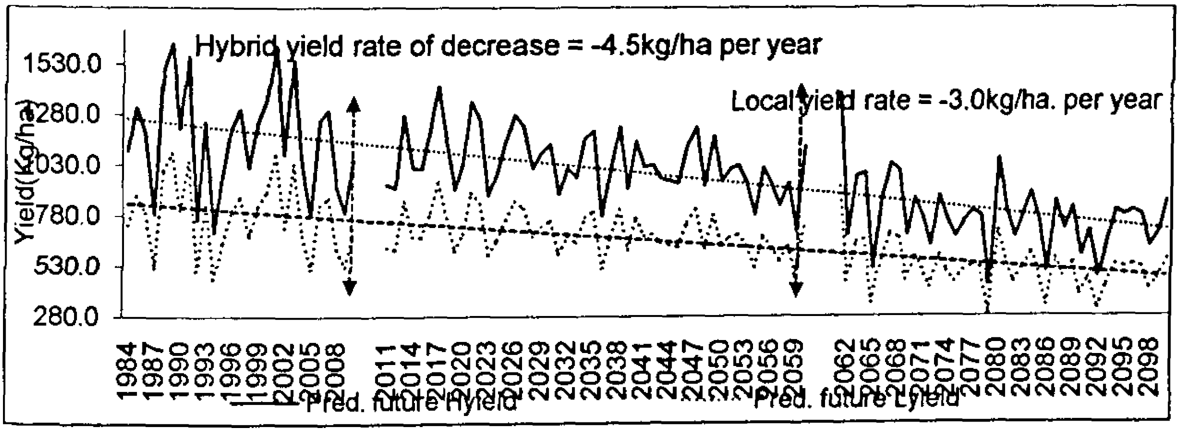


Figure 54 shows present and future projected sorghum yield for local and hybrid variety in the Shire Valley

The first column of Figure.54 as depicted by the arrow shows relation between yields simulated using observed climate data, the seconds and third columns are yields projected using future climate data sets from CSIRO Model. The general trend in this plots showed a decrease in the projected sorghum yield for both local and hybrid varieties. However, the rate of decrease was different from one another. Yield from hybrid variety decreased more than the local variety

(>1kg/year) as shown by the trend slopes in Figure.54. Given the existing and projected climate variables in the region, the model showed that temperatures, rainfall and radiation are good estimator of yield in the region. However, the weakness of the model is that it does not take into consideration other factors such as influence of fertiliser, weeds, pests, physiological stress of a crop to changes in the climate variables. Nevertheless, the results provided a better understanding of the relationship that exists between sorghum growth and climate variability. Relating the results for the time series of seasonal rainfall in the area, it can be concluded that whenever there was water stress leading to crop failure, similar variation was also observed in the sorghums yield, Figure.33.

4.6 Potential impacts of climate change on sorghum yield

4.6.1 Sensitivity Analysis of APSIM Sorghum Model

Sensitivity analysis was done to test yield response in the model to extreme changes in the climate variables. The test was done using both regression and APSIM Model and the results showed that increase in temperatures lead to decrease in yield. A temperature increase of 1.0°C decreased yield by 7.9 kg/ha; temperatures increase of 4.0°C resulted into yield decreased by 93kg/ha. The model was also tested by decreasing temperatures and the results favoured yield increase as shown by Table.31. A decrease of 5.0°C increased the yield by 97kg/ha Table 31. The results showed that there is an optimum temperature from which yield decrease. When test with a -10°C, a dramatic reduction in yield was observed. This analysis showed that increase in temperature of 1°C reduced yield by 11kg/ha per season.

Table.31 Summary of effect of temperature change on Sorghum yield in the Shire Valley

Temperature Change	Mean	Standard Error	Standard Deviation	Sample Variance	Minimum	Maximum	Confidence Level(95.0%)
Yield(-9°C)	1264.4	106.9	623.2	388330.8	0.0	2677.8	217.4
Yield(-8°C)	1354.1	69.8	407.0	165614.4	409.6	2047.7	142.0
Yield(-5°C)	1122.0	54.5	317.5	100811.7	421.5	1846.5	110.8
Yield(-3°C)	1077.8	57.7	336.4	113174.7	545.5	1822.8	117.4
Yield(-2°C)	1045.2	56.6	330.2	109012.7	536.7	1817.0	115.2
Yield(-1°C)	1035.1	56.1	327.2	107036.6	565.6	1779.2	114.2
Yield (0°C)	1025.0	54.6	318.2	101238.2	583.6	1783.2	111.0
Yield(1°C)	1017.1	53.5	311.7	97166.0	585.8	1794.5	108.8
Yield(2°C)	1013.4	55.9	325.9	106232.1	587.7	1905.1	113.7
Yield(4°C)	932.3	50.7	295.7	87432.2	333.4	1518.0	103.2
Yield(10°C)	391.2	30.5	178.0	31672.2	113.6	825.7	62.1

Note A change of 0°C represented a condition where no change in the existing present records was done.

When rainfall was increased by 20%, yield was reduced by 5% while a reduction in rainfall by 20% increased yield by 6%.(Figure.55) However, reduction in rainfall by 20% in the area implied that mean rainfall would be 563mm per season which is still an acceptable amount for sorghum growth; A 20% increase in rainfall resulted into seasonal mean rainfall of >845mm, but the soils characteristics of the areas as used by APSIM Model showed increase in percentage (60%) of clay soil. With such level of clay, infiltration rate would be low leading into water logging which result into poor aeration. When such conditions are prolonged, crop growth is retarded leading into poor yields. Increase in yield due to low rainfall was also observed by *Hazeltine,(1998)* who stated that sorghum can survive in low rainfall regions. However, temporal water excess followed by prolonged dry spell events lead to increased risk of soil moisture depletion as excess heating goes toward raising temperatures, increasing evaporation leading to plants wilting.

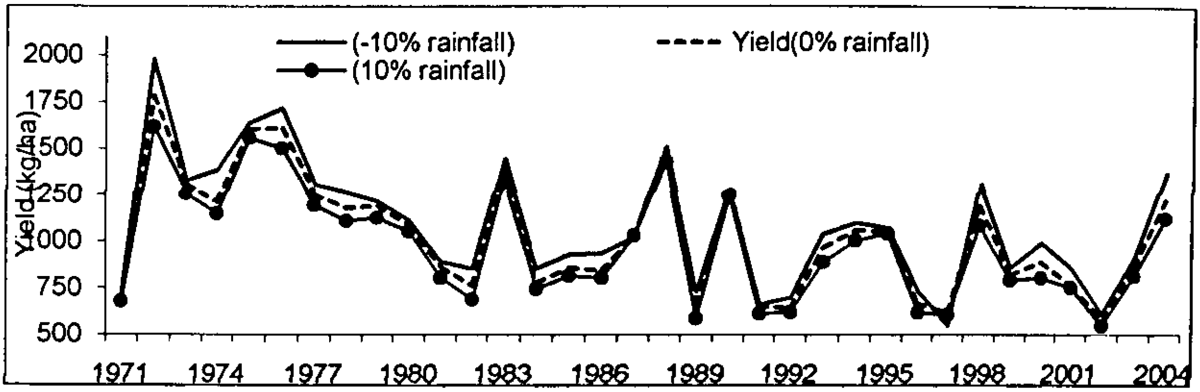


Figure 55 APSIM model yield response to changes in rainfall in the Shire Valley

4.6.3 Present and Future Trends in Sorghum Yield

4.6.3.1 Future effect of Climate Variability on Sorghum Yield

From the present study, simulation of sorghum yield using CSIRO-Mk3 output scenarios for the 21st century, showed a reduction in sorghum yield in the Shire Valley. Sorghum yield showed a *future reduction of between 5 and 9% during the 2020s and 2050s, and 14 and 63% in the 2080s.* When effects of the entire future climate elements was compared with the present, a decrease in yield was shown particularly where traditional way of farming would in practice. Yield under the effect of scenario A2, reduced more than yield obtained by scenario A1B. It was also observed that between 2046 and 2065 the effect will be severe than at the beginning and end of the 21st Century. The reason for stability in future yield loss is attributed to stability of green house gases which would be under control in scenario A2. With increase in Carbon Dioxide from 350ppm to 570ppm by 2050 and to 750ppm by 2070 rainfall distribution will also be affected. A project rainfall decline between 2-16% (2030 - 2100) will not have much effect at the beginning of the simulation period (2030s) (Table.30). With these conditions, the results from APSIM model demonstrated yield increase in the first part of the 2030 but a decline in the 2050s. The rate of decrease was huge towards the end of the 2100 where yield was shown to decrease by over 40kg/ha of land per year.

4.6.3.2 Effect of Climate variability on sorghum yield 1984-2004

Figure.56 shows comparison between simulated yields under 0kg/ha, 25kg/ha and 50kg/ha fertilizer management strategies and observed sorghum yield. Observed yields were less than simulated yields by 14% (25kg/ha fertilizer), 63% (50kg/ha fertilizer) when hybrid variety was used.

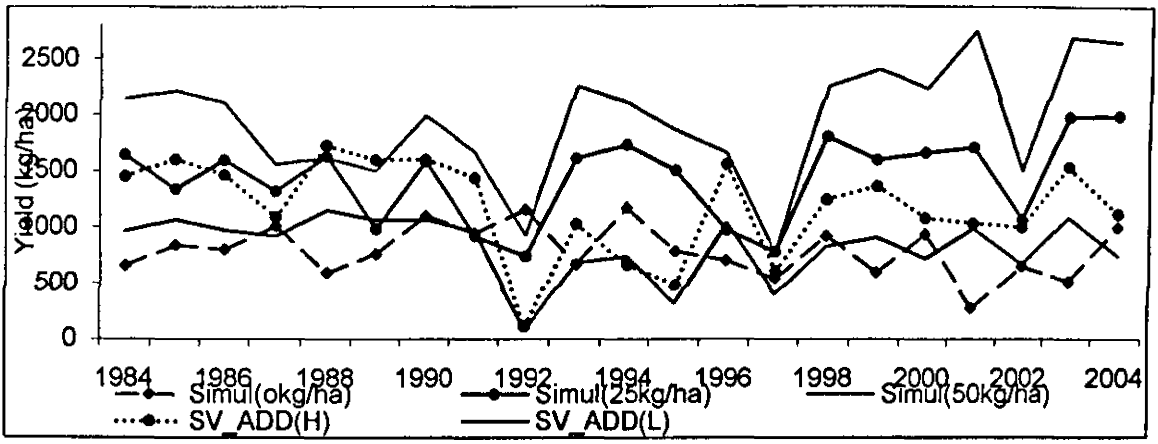


Figure 56 Comparison of the effect of climate variability on sorghum yield.

4.6.3.3 Effect of Rainfall on sorghum yield

Rainfall increase in a season resulted in increased sorghum yields while decreased rain resulted in low yields (Figure.55). As the total seasonal rainfall increased, the final yield increased this also showed the association that existed between sorghum and yield. An unexpected finding in this study was that sorghum yields varied more between years of rainfall events than within years under more or reduced rains. Simulated yields showed that with increase in rainfall in the area, sorghum yield decreased while with decreased rainfall, the yield increased sharply, Table.32.

Figure.57 shows the effect of change in rainfall over the Shire Valley. A 16% decrease in rainfall showed a decline in the sorghum yield between 2046-2100. The decrease was so dramatic in the yield when there was no fertilizer application. The yield time series pattern revealed magnitude of climate variability impacts in the future by the decrease of (43kg/ha per year) between 2081-2100. Table 33 shows statistical summary of fertilised sorghum yield under these conditions. More rainfall was shown to have negative effect on the yield as seen in Table.32 where a 20% increase in rainfall reduced yield by about 100kg/ha.

Table 32: change in yields as results of percentage change in daily rainfall.

Table.32.	*(-20% rainfall)*	*(-10% rainfall)*	*(-5% rainfall)*	*(0% rainfall)*	*(5% rainfall)*	*(10% rainfall)*	*(20% rainfall)*
Mean	1144.8	1086.0	1050.7	1025.0	1000.9	975.0	924.2
Std. Deviation	362.7	339.1	332.1	318.2	306.4	300.4	284.5
Sample Variance	131568.8	114959.1	110306.1	101238.2	93905.9	90226.7	80922.4
Minimum	546.6	550.0	555.3	583.6	559.3	551.4	525.1
Maximum	2136.2	1980.1	1882.5	1783.2	1695.4	1620.5	1490.9
Conf. Level(95.0%)	126.6	118.3	115.9	111.0	106.9	104.8	99.3

Table 33 summary statistics of simulated and observed sorghum yield in the Shire valley

Table33	*Simul(okg/ha)*	*Simul(25kg/ha)*	*Simul(50kg/ha)*	*SV ADD(H)*	*SV ADD(L)*
Mean	793.0	1434.8	1943.3	1180.5	828.6
Standard Error	50.4	83.0	115.0	93.4	60.7
Standard Deviation	231.0	380.2	526.8	428.2	278.4
Sample Variance	53350.3	144558.8	277546.6	183377.2	77493.9
Conf. Level(95.0%)	105.14	173.07	239.81	194.93	126.72

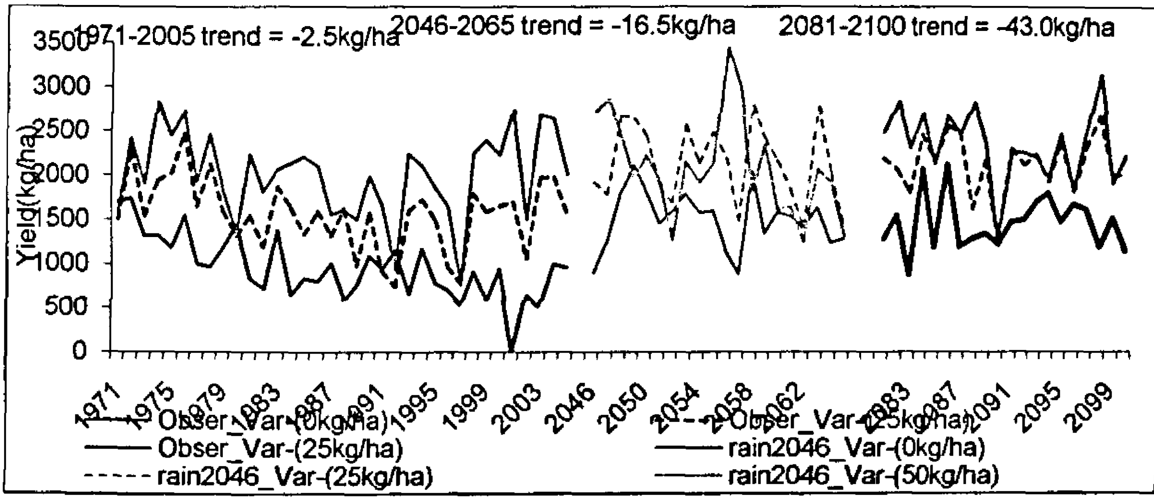


Figure 57 APSIM Simulation Effect of rainfall variability and change (decrease) on Sorghum yield

4.6.3.4 Effect of Temperature increase on sorghum yield

Sorghum yields increased in decreasing temperature until about 10°*C* but in temperatures below this threshold, temperatures quickly became very harmful, and the slope of the decline above the optimum is significantly steeper (Table.32.). It was also observed that during years of low rainfall, temperatures increased. So, warmer temperatures in a season resulted in lower yields and during the summers of 1992 and 2000, sorghum yield decreased despite increase in rainfall due to increase in temperatures (Figures.17 and 56).

In Figure.58 for period 1971-2004, 2001-2065 and 2081-2100, yield increased during the 2046-2050 periods and decreased again beyond 2065. The reason to the decline can be associated with effect of increase future temperature. The first portion of Figure.58 shows effects of the observed temperatures variability while second and third portions show future response of yields to effects of temperature change of 1.6°C maximum temperatures and 1.8° minimum temperatures.

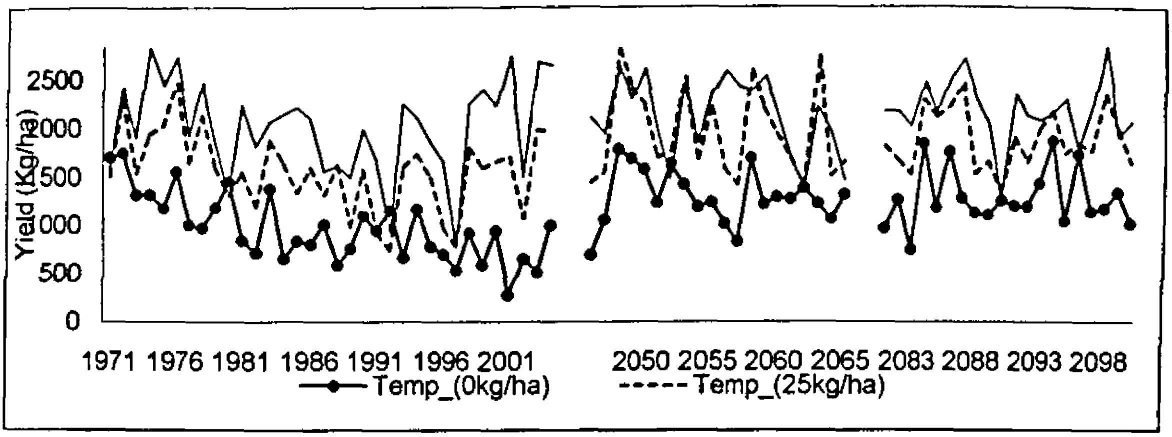


Figure.58 APSIM simulation Effect of present and future temperature variability and change on Sorghum Yield

4.6.3.5 Effect of Climate Change (CC) on Sorghum Yield

Figure.59 shows variability of sorghum yield at three fertilizer management levels in response to variability in the climate elements for present and future. The first segment of the graph shows the variability due to observed records, second segment shows variability due to near future (2046-2065) while the last segment shows variability due to future change in the climate elements (variables). Overall trend shows increase in the yield but trend by segment shows decrease in yield for 0 and 25kg fertilizer application from 2050s.

Comparison of present and future sorghum yield as a result of the climate change on sorghum was evaluated through simulating yield using individual future climate element, (Table.34). Combined effect of all climate elements resulted into yield drop of 2.7% by 2065 and 1.2% by 2100. However increased temperatures and Carbon Dioxide resulted into increased sorghum yield between 36-56% particularly when no fertilizer was applied. A decline in yield was observed when fertilizer was included at sowing. This dramatic decline in yield is probably due to temperature influence as explained in (Figure.61 and Table.30). The findings are supported by Reeves, et al.,(1994) who found that when sorghum is grown under increased carbon dioxide, its dry matter reduces causing its yield to decrease and its alter the leave nitrogen content.

Table 34: Percentage Change of yield due to effects of climate change and Carbon Dioxide

	Climate Change			Carbon		
	Yield _CC (0kg/ha)	Yield _CC (25kg/ha)	Yield _CC (50kg/ha)	*Yield_2xCO_2 (0kg/ha)*	*Yield_2xCO_2 (25kg/ha)*	*Yield_2xCO_2 (50kg/ha)*
2046/2065	51.2	23.2	-2.7	40.2	35.8	21.9
2081/2100	30.4	19.6	-1.2	24.0	23.3	17.2

CC represents a scenario where effects of all the climate elements are incorporated.

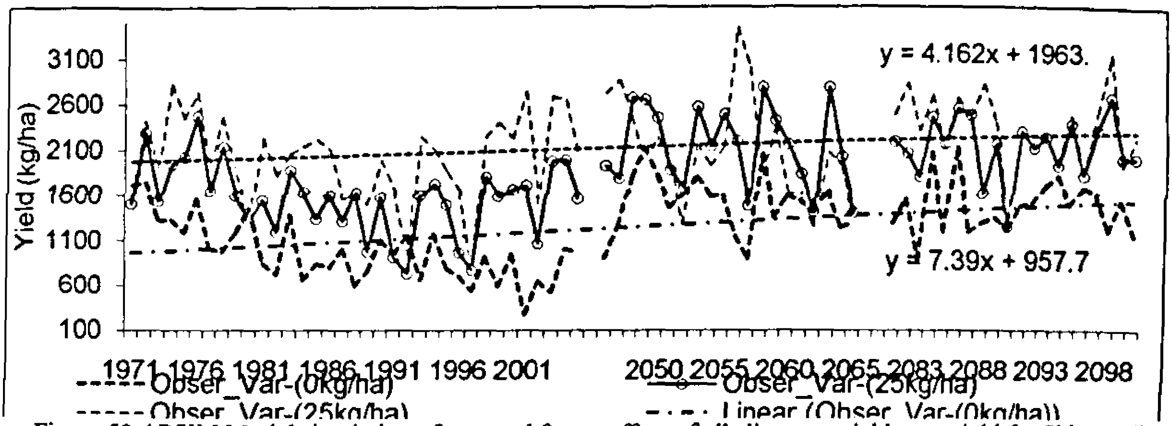


Figure 59 APSIM Model simulation of past and future effect of all climate variables on yield for Shire Valley 1971- 2100

4.6.3.6 Effect of Carbon Dioxide increase on sorghum Yield

Figure.60 below shows the effect of carbon dioxide on sorghum yield in the Shire Valley. Sorghum yield without fertilizer application will be significantly reduced ($p<0.005$) in the near future as doubling Carbon Dioxide concentration will have no beneficial effect to the crop. Nevertheless, the effect of Carbon dioxide will be minimal as compared to the effect of temperatures alone but more than the effect of rainfall.

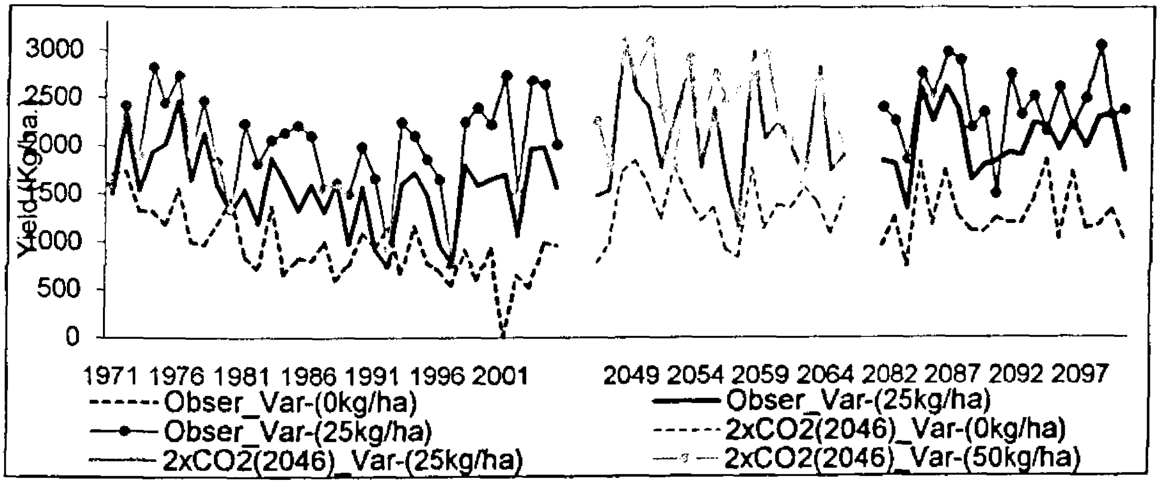


Figure 60 APSIM Simulated Yield Future effect of Carbon Dioxide on Sorghum Yield

Table 35: Percentage (%) Change of Sorghum Yield with respect to Climate Changes

	Temperature			Rainfall		
	Yield_Temp (0kg/ha)	*Yield_Temp (25kg/ha)*	*Yield_Temp (50kg/ha)*	*Yield_Rain (0kg/ha)*	*Yield_Rain (25kg/ha)*	*Yield_Rain (50kg/ha)*
2046/2065	36.47	26.65	5.87	55.9	36.6	4.6
2081/2100	25.14	16.38	8.19	34.4	26.6	14.2

From Table 35, summary of the effect of temperatures and rainfall on sorghum yield is given. The results from the analysis showed that an increase in temperature from 26.7°C to 30.3°C decreased yield by 4% when averaged across fertilizer application managements, Figure.61 & 62. When an assumption of higher CO2 levels direct effect was incorporated, sorghum yield increased significantly (Cox Stuart test, (P< 0.03) across all temperature ranges by about 13.4% in the near future (2046-2065) but the increase dropped to 5.6% in 2100.

The major cause for this change in impact is that sorghum belongs to C4 photosynthetic plant which is disadvantaged at higher levels of carbon concentration because photorespiration is reduced and the additional ATP cost of C4 photosynthesis makes it less efficient, *(Ehleringer, et al., 2002)*. A linear decrease was observed (P < 0.05) in locally variety yield at increased rates of fertilizer management with increase in temperature from 29.5°C to 33.3°C during OND and 26.7°C to 30.3°C during JFM. The percentage decrease in yield due to increase in temperatures was greater at the highest temperature (33.3°C). There was no combined contribution between temperature and CO_2 in promoting yield. The reason for the lack of contribution is probably due to stomata closure at high temperatures leading to reduction in conductance and leaf photosynthesis as observed by *Reeves et al, (1994)*. *Tubiello et al., (2000)* also found that combined effects of elevated atmospheric CO2 and climate change would reduce crop yields if cropping style maintains the current management practices. Reeves found that high concentration CO_2 increases growth by lowering stomata conductance and increased water-use efficiency. So in a water limiting areas like Shire valley, future potential yield of sorghum will be negatively affected by high CO_2.

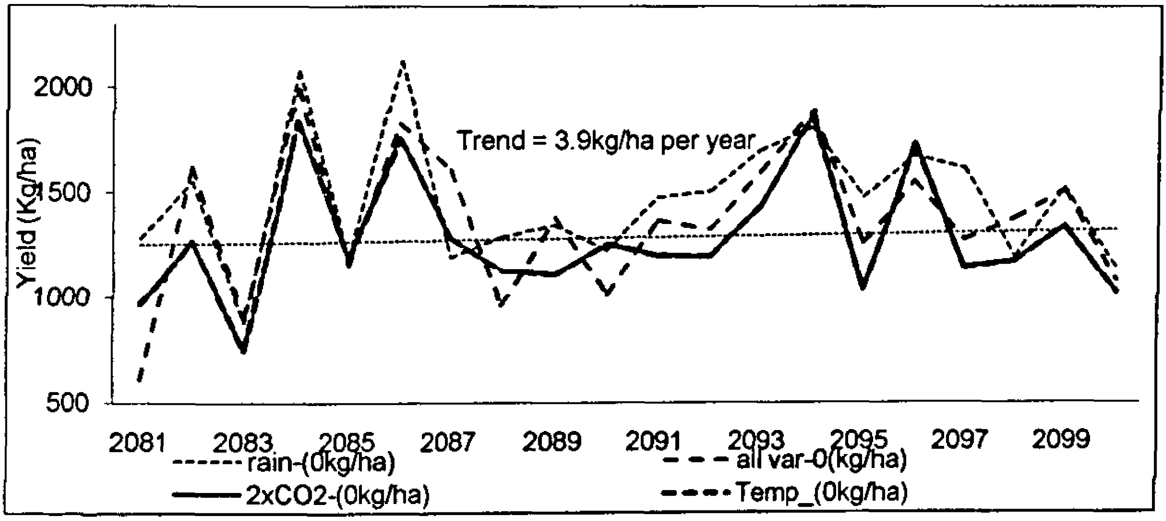


Figure 61 APSIM simulation of future effect of various climate variables on Sorghum Yield grown under no fertilizer.

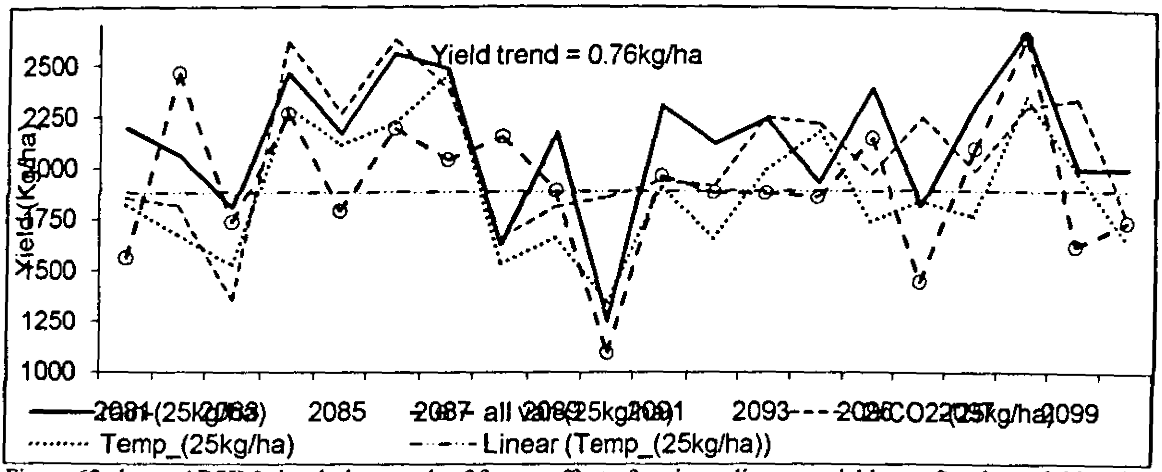


Figure 62 shows APSIM simulation result of future effect of various climate variables on Sorghum yield under 25kg/ha fertilizer

4.6.3.7 Variability and Trends of Present and Future Potential Yield

The variability of rainfall both in time and in space across the region directly influences the availability and variability of surface and groundwater resources which result into affecting sorghum growth in the region. From regression results Figure.52; it was shown that as increase in temperatures and decrease in rainfall continues, sorghum yield would be severely be affected. Future temperatures for Shire valley are expected to increase by 15% and 13% for JFM and OND respectively. With such increase, sorghum production in the area would experience water stress during the critical period of growing season (JFM) due to increase in evapotranspiration caused by high temperatures. A temperatures decrease of -3°C for JFM in Shire Valley would results in the seasonal mean temperatures change of 24.2°C and 27.3°C for OND; temperatures increase of 4°C by 2100 would results into seasonal mean temperatures of 31.2°C for JFM and 34.3°C for OND.

Several global climate models indicated that the future mean climate base state could more resemble an El Niño–like state (i.e., a slackened west–east SST gradient with associated eastward shifts of rainfall), though the result remains model dependent. For such an El Niño–like climate change, future seasonal rainfall extremes associated with a given El Niño would be more intense due to the more El Niño–like mean base state *(Meehl, et al., 2000)*. For Shire valley, El Niño-like climate change would mean increase droughts and prolonged dry spell.

So with these temperatures changes sorghum production would be negatively affected mainly due to increase in the rate of evaporation which will cause water stress in the plants, pollen viability which will results into infertility hence low yields. According to *Jing Wang et al.,(2009)*, increase in temperatures shortens the length of the growing season, further increase promotes incraese of evaporation from soil surfcae and reduce crop water use. The temperature increament would increase the impact of rainfall changes *[ibid]*. Nevertheless, high temperatures would promote vegetative growth in the plant hence giving advantage to industry that uses the crop as feeds.

The analysis also showed that normal rainfall years have significantly decreased while numbers of wet years have increased over Makhanga and Nchalo but decreased over Ngabu. 1975-1989 periods were wetter than all the other years and Ngabu was wettest among all the station. Rainfall from all the study sites was decreasing insignificantly ($P<0.05$) while it was more unpredictable at Ngabu and Chikwawa during October to December than other stations. Similarity in the behaviour of variability and rainfall distribution were found at Makhanga and Nchalo except for the tendency of Nchalo to get excess rainfall. Generally, rainfall and temperatures variability in the area is marred by increase in extreme events. Most stations indicated a positive sign of increasing trend of drier conditions while extremity in heavy rainfall increased. Decrease in rainfall and increase in temperatures also imply increase in the eva-transpiration rate and hence reduction in photosynthesis processes. These events directly affect the crop growth through enhancing weeds growth and promotion of the spread of pests and diseases.

The effect of this variability on sorghum yield was shown by correlating yield to climate variability. The results further indicated that rainfall had a significant negative correlation with sorghum yield. This implied that increase in rainfall in the area would lead to reduction in yield probably due to water logging and rotting. A significant trend was observed in both seasonal rainfall and sorghum yield which indicated the significance of the role played by climate variables in the production of sorghum. Decreased trend in rainfall was observed to contribute negatively to sorghum yield. Predicted yield in the Shire Valley showed a significant decreasing trend which may strongly be associated to the impact of climate variability on the soil water as well as evaporation rate hence influencing crop metabolism processes.

4.6.3.8 Yield, APSIM and Regression Model Performance.

Further than this, yield for the two varieties were compared to find out the variety which is superior in its response to climate variability in the areas. The results from analysis of variance of the two variety showed that there are significant effects of climate variables among the two varieties (F statistic = 32.12, P-value = 1.617e-07). This implied that the mean yield was significantly different for the two varieties of sorghum; therefore hybrid variety (1) in Table 36 was significantly superior to local variety in its response to the changes in the climate variables.

Table 36: Analysis of variance showing differences in mean yield by variety

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Variety	1	3892015	3892015	32.117	1.617e-07 ***
Group	1	0	0	0.000	0.9998
Residuals	93	11270	121183		

The model performances were also used to compare fertilizer management practices that would optimise yield. The RMSE and d for the model and observed are given in Tables.37.

Table 37:Comparison of APSIM Model Simulated Yield and Observed Yields

	Hybrid variety			Local variety		
Fertilizer	0kg/ha	25kg/ha	50kg/ha	0kg/ha	25kg/ha	50kg/ha
RMSE	0.494	0.479	0.530	0.589	0.738	1.178
d	0.549	0.352	0.452	0.433	0.327	0.383

Note Results from Table.37 were first transformed by log (base 10) before RMSE and d was calculated.

Table.38 shows results from regression equation of sorghum yield and climate variable. A quantitative assessment of the APSIM model also showed that the model output agreed with the observed data. Performance measures were evaluated to give the quantitative measure of the model. The results showed that the model performance was good shown by RMSE in Table.37 and index of agreement (d) in Table. 37.

Table 38: Comparisons of Regression Model predicted yield and observed Sorghum Yield

RMSE	0.557	0.4305
d	0.7725	0.5930

When compared to the regression model developed, the results showed that APSIM model is a better model for predicting yield than regression equations. However, in the absence of crop models, regression equations can be useful tool in predicting yield in the area. Multiple regression analysis showed climate variables (total rainfall, solar radiation, minimum and maximum temperatures) accounted for 86.7% of the variation of Sorghum yield in the Shire Valley. It was also observed during sensitivity analysis that the model was sensitive to change in climate variables particularly temperatures and rainfall. Overall performance showed that APSIM model performed well on sorghum yield for Shire valley. Thus, it can be used to predict yield response to climate variability and change in combination with alternative management styles in the area. Given GCM model uncertainty on the grid structure and boundary of a study area, the simulated results suggest that the model is ideally viable for assessment of the effect of change in climate variables to sorghum growth and yield on daily, monthly and annual time scales. The performance of the model can be improved by using climate, crop and soil data obtained from experiments and at a specified site within a region. Results further revealed that APSIM Model can work better with accurate and reliable climate data records, soil data for the area of study and data from existing management practices where the simulated crop is grown. The response of yield in the model during the development and vegetative phases depends on the climate variables. If data used in simulating yield is largely from estimates, then yield output would also be underestimated. In addition to this, influence of spatial variability on yield may lead to wrong yield representation especially when mixing effects of factors cancel each other in case of areal average representation of the climate elements. Basing on other studies done on sorghum, more rainfall increases the variability of sorghum yields, which is not surprising given the tolerance of sorghum to dry conditions *(Dimes, et al, 2009).* Higher temperatures decrease the variance of sorghum yield in response to geographic distribution of temperature in the Shire Valley. According to *Vara Prasad (2006),* delay in panicle initiation and flowering of sorghum is caused by the combined effects of high CO_2 and warmer foliage temperature. However, increased carbon dioxide would reduce plants water demand thereby reduce the impact of rainfall on crop yield, *(Yu-Min Wang, et al (2009). Folliard, et al., (2004)* mentioned that modeling sorghum in response to temperatures is always problematic, and is often not sufficient to accurately predict the final yields in high temperatures environments. In addition to this, high yields in sorghum depend on the fact that the shoot of the crop maintains its water status and turgor maintenance under drought stress, *(A Blum, 2005).*

Despite the success in maintaining sorghum yields at present management practices and the existing climate variability conditions, results showed that yields will decrease under future climate change conditions possibly due to increased water stress. Eva-transpiration rate linked to higher temperatures and prolonged dry spells would also be exacerbated hence negatively impacting the yield. When climate change with adaptation is considered simulation for 25-50kg/ha of fertilizer was required to maintain an optimal sorghum yield at current levels. These findings suggest that promotion of optimizing sorghum production in the areas should not only focus on the yield realized by farmers, but they should also include incentives of some kind to comprise farmers' productions loses from other cereals. Incentives such as seeds availability and fertilizer revolving funds for farmers can better trade-off. These are some of the factors that influence farmers' decision making and promotes profitability.

CHAPTER FIVE

5.0 Summary, Conclusion and Recommendations

This chapter summarizes the conclusion that can be drawn from the results and discussion in chapter 4 and proposes several recommendations for future works.

5.1 Summary

Crop production in the Shire Valley has become very risky always resulting in low and very variable yields. This is caused by severe water deficits during the crop growing period due to prolonged dry spells and increased frequency of droughts. Increase in population growth rate has also placed a heavy burden on land and water resources leading to expansion of cultivation to marginal areas. Limited knowledge on dry land farming and the impact of land use on the resources by the local community has exacerbated climate change impact. With projected increase of temperature by 9% by 2060, food insecurity in Malawi would rise. Therefore, this study was undertaken to examine the impact of changes in the climate variables and management practices (with and without fertilizer, with and without crop residues) on sorghum production in the Shire Valley. Agricultural Production Simulator (APSIM) model was adapted for simulating the effect of climate variables in the growth and production of sorghum in the study area. The adapted model was then used to look at the impact of the changing climate variables on growth and production of sorghum.

The study investigated 52-years rainfall data from 1960 to 2011, and 34 years of temperatures from 1971-2004 from five and two meteorological stations respectively. Summaries of climate statistics were calculated to help explanation and in the determining the significance of each climate elements effects. Positive (negative) trends in temperatures (rainfall) indicated the strength of climate change the effect of in the area. Analysis of extreme climate also revealed unpredictability of climate elements where it was shown that crop growing length was shortening, number of consecutive dry days (CDD) and reduction in rainydays had increased. Alternating patterns of extreme wet and extreme dry years were also observed. The rainfall had firm persistence i.e. wet and dry periods, while the temperature has no firm persistence. The absence of persistence in temperatures indicated its relationship to altitude and winter systems that affect the area. A strong seasonal and inter-annual variations was also observed in both temperature and rainfall (Figure.18 and 28) due to influence of rain bearing systems such as ITCZ, easterly waves, cool southeasterly winds and Tropical Cyclones. The positive trends of temperature generally opposed those of rainfall. Both the year 1992 and 2002 experienced low rainfall and cold winter temperatures, which were shown by low rainfall in October to March and in very low temperatures from April to May. The growing season in 1992 corresponded to low level of yields in this year, but the case in 2002 was somewhat different indicating that decrease trend in the yields was explained the trend in the extreme rainfall and temperatures events. On the other hand, variation of winter temperature can be explained by the influence of high pressure systems (position and strength) in the Indian Ocean during April to August. Some variation particularly summer temperatures were associated with land use and geographical features of the areas.

The study found that rainfall is distributed over 6months (375 mm – 610mm) in a season. Its variability had the more influence in sorghum production in the areas as in the case of 1992. The distribution pattern also revealed increased variability during the onsets of the season (OND), rainfall amount and. The distribution during this period showed the important consequences of rainfall variability on crop production as reflected in the yields time series. Within a crop growing period, total rainfall could be as low as 143mm and as high as 1115mm and the differences in total rainfall resulted in crop yields results differences. The importance of seasonal rainfall varied over space, affecting the growing pattern, as depicted by low yield for Nsanje EPA. Low mean temperature (18°C to 20°C) prolonged the growing duration thereby increasing the chance of pests and fungal damages especially in the southern part of the area (Nsanje District) where absolute minimum temperatures were lower. Crop growth varied from season to season as dictated by both temperature and rainfall distribution during the growing period. With good rainfall distribution, sorghum attained good yields, however, in seasons with poor rainfall distribution such as 1992, growth was very poor and in some seasons, the crop died completely which led to poor yield as well. The study further revealed that future climate impacts on sorghum production would be worsened by increase in climate variability as demonstrated by CSIRO Model out for scenarios A2 and A1B. Both scenarios presented a declining (increase) trend for rainfall (temperatures).

For sorghum production, two varieties and three fertilizers management strategies were used to simulation yield using APSIM model. The evaluation and modification of the model focused on change in the climate variables and sorghum yield. Final APSIM model yield results showed a good correlation ($r = 0.897$ for local variety and 0.902 for hybrid yield) between observed and predicted yields. However, the model performance demonstrated that it was more sensitive to the effect of climate elements particularly minimum temperatures and rainfall simulating sorghum yield. APSIM proved to be a flexible simulation tool with the capability to alter management styles, especially under dry and limiting production conditions where it is more applicable. Results from both regression and APSIM model showed that both inter- and intra-seasonal changes in rainfall and temperature are linked with changes in the two varieties of sorghum yield. Similar to previous studies (*Rowhani et al., 2011; Semenov, 2009*), this study showed that sorghum yields increased with increased seasonal rainfall and decreased with higher temperatures. Increased rainfall variability during the growing season reduced yields for sorghum and that increased exposure to extremes condition resulted into crop damages. *Rowhani et al., (2011)* demonstrated that increased temperature and rainfall variability would reduce crop yields.

The simulation results also showed that influence of rainfall could be exacerbated by increase in carbon dioxide concentration. As noted in other researches, changes in CO_2 would affect near surface temperature by modifying it thereby reducing the supply of moisture for rainfall *(Cox, et al, 2000)*. Considering that sorghum undergoes C4 photosynthesis, altering its photosynthetic pathways would lead to different responses of transpiration when temperature is increased. Therefore, doubling CO_2 would reduce sorghum production through the decrease of stomata opening where near-surface air temperature has been increased, *(Betts et al., 2005)*.

The results also showed that simulating a crop yield without applying fertilizer in the area is equivalent to application of 16.5kg/ha of UREA in APSIM model. RMSE results suggested robustness of APSIM Model in its use to simulated growth and sorghum yield in the Shire valley. Using field yields and climate data for each growing season and by allowing on farm management changes in the area, it is possible to reduce sorghum production simulating uncertainties related to the model use. Therefore the current model requires improvement in simulating the effect of soil fertility on crop production in the Shire Valley. Further investigations on residues decomposition and their effect on final yield, soil evaporation and soil water content is required. Assessments of climate change impacts in the Shire valley should also take into account the effects of land cover changes on climate.

5.2 Conclusion

The study has shown that yield loss under changing climate elements will be severe in the near future. However, use of fertilizer and residuals management demonstrated a positive potential in reversing the loss. Crop residuals would enhance sorghum ability to withstand drought hence promoting yield increase with minimum rainfall in the area. It was also shown that temperatures drastically increase soil water loss through eva-transpiration and this accounted for 15% and 17% total yield loss for local and hybrid yields respectively. This shows that Shire valley has become a very risky production environment for cereal crops as a result of frequent droughts. On average, rainfall decrease accounted for 65% loss of total yield in local variety and 45% of the hybrid variety, hence 20% more loss under local variety. Considering future climate changes as shown by both scenario A2 and A1B, it is appropriate to consider management strategies such as fertilizer application and post harvesting management (leaving crop residuals in the field). These findings suggest a potential economic benefit from fertiliser application and residuals in the area even with projected future increase in climate variability of summer rainfall and temperatures.

5.3 Recommendations

The study recommended that the knowledge and experiences gained from this study be extended on farm. This can be done through participatory on-farm research between farmers, extension officers and researchers. Simulation model (APSIM) can be used to assess and screen different crop management practices before they are tested on farm. Since APSIM Model has proved to be an excellent tool for crop production management, it is therefore recommended that further work be done using field study to improve its performance. Further recommendations include, assessing the applicability of satellite data products in the simulation of crop production in the area. This would be useful in areas where meteorological weather stations are not available. There is also a need to enhance areal data monitoring and collection, particularly radiation, temperatures and wind data. In addition to this, I suggest that climate data records be updated following different data formats as required by different physical and biological models such as APSIM Crop Model in order to increase its applicability. Finally, to increase usage of research results, it is further recommended that the results from this study be translated to user friendly formats and shared through different avenues. It is useful to use research results and decision support tools in assessing, developing and promoting production improvement strategies at policy level.

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APPENDIX

A R code used for trend test using Cox-Stuart Test

```
-----------------------------------------------------------------------
> cox.stuart.test =function (x)
{ method = "Cox-Stuart test for trend analysis"
 leng = length(x)
 apross = round(leng) %% 2
 if (apross == 1) {
  delete = (length(x)+1)/2
   x = x[ -delete ]  }
  half = length(x)/2
 x1 = x[1half]
  x2 = x[(half+1)(length(x))]
  difference = x1-x2
  signs = sign(difference)
signcorr = signs[signs != 0]
 pos = signs[signs>0]
 neg = signs[signs<0]
  if (length(pos) < length(neg)) {  prop = pbinom(length(pos), length(signcorr), 0.5)
   names(prop) = "Increasing trend, p-value"
rval <- list(method = method, statistic = prop)
  class(rval) = "htest"
return(rval) }
else { prop = pbinom(length(neg), length(signcorr), 0.5)
  names(prop) = "Decreasing trend, p-value"
 rval <- list(method = method, statistic = prop)
 class(rval) = "htest"
return(rval) } }
-----------------------------------------------------------------------
```

B DEFINITIONS OF SOME TERMS

Extreme Indices Characterisation

1. **CSDI, cold spell duration index** count of days in a span of at least six days where TN ≥ 10^{th} percentile.

   Let TN_{ij} be the daily minimum temperature on day *i* in period *j* and let $TN_{in}10$ be the calendar day 10^{th} percentile of daily minimum temperature calculated for a five-day window centred on each calendar day in the base period *n* (1971-2000). Count the number of days where, in intervals of at least six consecutive days $TN_{ij} < TN_{in}10$.
2. **R10mm, heavy rainfall days** count of days where RR (daily rainfall amount) ≥ 10 mm.

   Let RR_{ij} be the daily rainfall amount on day *i* in period *j*. Count the number of days where $RR_{ij} \geq$ 10mm.
3. **R20mm, very heavy rainfall days** count of days where RR ≥ 20 mm.

   Let RR_{ij} be the daily rainfall amount on day *i* in period *j*. Count the number of days where $RR_{ij} \geq$ 20mm.
4. **Rnnmm** count of days where RR ≥ user-defined threshold in mm.

   Let RR_{ij} be the daily rainfall amount on day *i* in period *j*. Count the number of days where $RR_{ij} \geq$ nnmm.
5. **CDD, consecutive dry days** maximum length of dry spell (RR < 1 mm).

   Let RR_{ij} be the daily rainfall amount on day *i* in period *j*. Count the largest number of consecutive days where $RR_{ij} <$ 1 mm.
6. **CWD, consecutive wet days** maximum length of wet spell (RR ≥ 1 mm).

   Let RR_{ij} be the daily rainfall amount on day *i* in period *j*. Count the largest number of consecutive days where $RR_{ij} \geq$ 1 mm.
7. **WSDI, warm spell duration index** count of days in a span of at least six days where TX ≥ 90^{th} percentile.

   Let TX_{ij} be the daily maximum temperature on day *i* in period *j* and let $TX_{in}90$ be the calendar day 90^{th} percentile of daily maximum temperature calculated for a five-day window centred on each calendar day in the base period *n* (1971-2000). Count the number of days where, in intervals of at least six consecutive days $TX_{ij} \geq TX_{in}90$.

Regression equation for Model output data correction

Daily Data mapping

1.) *Ngabu_Tmax_fsct=9.00401+0.82072*CSIROtmax,*
R-squared **0.703**, Adjusted R-squared 0.703; F-statistic **1.38e+04, p-value <2.0e-16**

2.) *Ngabu_Tmin_fsct=0.94777+0.92721*CSIROtmin,*
Multiple R^2-squared **0.718**, Adjusted R^2 **0.718;** F-statistic **1.49e+04, p-value <2.0e-16**

3.) *Ngabu_Rain_Fsct=0.07755+0.5779*CSIROrain,*
R-squared **0.152,** R^2 0.152; F-statistic **1.05e+0, p-value <2.0e-16**

Monthly data mapping

4.) *Makhanga Fcsted Max-Temp= -12.8028+ 1.4723* CSIRO MK 3.6.Makhangatmax*
R^2=0.7822, F statistic=143.6, **p-value** ***8.138e-15***

5.) *Ngabu Fcsted Max. Temp=-18.8004+1.6683*CSIRO MK 3.6.Ngabutmax*
R^2= 0.8152; F-statistic= 141.1, p-value 2.855e-13

....

1. Regression Model results Predicted Sorghum Yield

*i) SVLocal = 7289.2-4.599*Seastmax + 0.1642*Seasrain -63.85*Seastmin. Residual standard error 198 on 10 degrees of freedom; Multiple R-squared 0.8037, Adjusted R-squared 0.5486 ,F-statistic 3.15 on 13 and 10 DF, p-value 0.03809*

*ii) SVHybrid = 11124.7-22.26*Seastmax + 0.2197* Seasrain – 86.62 * Seastmin. Residual standard error 279.9 on 10 degrees of freedom, Multiple R-squared 0.8146, Adjusted R-squared 0.5736, F-statistic 3.38 on 13 and 10 DF, p-value 0.03033*

Where

- SVLocal= Shire Valley Local Variety
- Seasonaltmax= Seasonal maximum temperatures
- Seasonaltmin=Seasonal minimum temperatures
- Seasonalrain=seasonal rainfall

C Tables.

Table 39:OND Mean Dekadal Rainfall(mm) for Shire Valley stations

	October			November			December		
OND	**dek1**	**dek2**	**dek3**	**dek1**	**dek2**	**dek3**	**dek1**	**dek2**	**dek3**
Nsanje	7	7	20	25	38	32	58	66	78
Ngabu	5	6	10	18	10	29	62	57	72
Nchalo	5	6	23	24	8	9	55	56	47
Chikwawa	6	3	10	10	20	33	52	59	65

Table 40:OND Mean Dekadal Rainfall(mm) for Shire Valley stations

JFM	January			February			March		
	dek1	ek2	dek3	dek1	dek2	dek3	dek1	dek2	dek3
Nsanje	66	60	56	45	81	34	62	37	30
Ngabu	58	40	41	62	58	47	46	50	41
Nchalo	51	37	42	58	70	43	37	23	28
Chikwawa	64	51	65	53	55	28	48	43	27

Table 41: Summary of regression results of future rainfall for Shire Valley

2001-2030	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Mean	**230.9**	**175.9**	**132.8**	**44.5**	**18.8**	**15.7**	**16.8**	**6.2**	**5.0**	**21.0**	**72.6**	**221.9**
Standard Error	0.70	3.29	0.09	0.29	0.38	0.08	0.51	0.07	0.07	0.00	0.33	1.91
Median	230.9	180.7	132.8	44.3	19.4	15.8	16.4	6.3	5.1	21.0	72.8	221.1
Standard Deviation	3.85	18.02	0.48	1.57	2.10	0.41	2.79	0.38	0.39	0.01	1.80	10.47
Sample Variance	**14.78**	**324.68**	**0.23**	**2.47**	**4.41**	**0.17**	**7.81**	**0.14**	**0.15**	**0.00**	**3.24**	**275.22**
Conf. Level(95.0%)	1.44	6.73	0.18	0.59	0.78	0.15	1.04	0.14	0.15	0.00	0.67	3.91

2031-2060	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Mean	**231.5**	**172.1**	**132.9**	**44.2**	**19.2**	**15.6**	**17.0**	**6.3**	**5.1**	**21.0**	**72.5**	**218.7**
Standard Error	0.8	3.3	0.1	0.3	0.4	0.1	0.6	0.1	0.0	0.0	0.4	3.2
Median	231.1	172.3	132.9	43.8	20.0	15.7	15.9	6.4	5.2	21.0	72.8	218.3
Standard Deviation	4.57	17.83	0.36	1.63	2.37	0.56	3.06	0.44	0.26	0.01	2.07	17.43
Sample Variance	**20.92**	**317.79**	**0.13**	**2.64**	**5.61**	**0.31**	**9.39**	**0.19**	**0.07**	**0.00**	**4.29**	**303.84**
Conf. level(95.0%)	1.71	6.66	0.13	0.61	0.88	0.21	1.14	0.16	0.10	0.01	0.77	6.51

2061-2090	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Mean	**231.11**	**169.19**	**132.72**	**43.95**	**18.72**	**15.77**	**15.55**	**6.28**	**5.14**	**20.96**	**72.43**	**222.35**
Standard Error	0.58	2.91	0.09	0.21	0.37	0.06	0.37	0.07	0.03	0.00	0.40	2.00
Median	231.36	168.13	132.86	43.75	19.39	15.84	14.94	6.50	5.23	20.95	72.56	220.89
Standard Deviation	3.70	18.62	0.58	1.35	2.36	0.41	2.39	0.46	0.22	0.01	2.59	12.79
Sample Variance	**13.68**	**346.67**	**0.34**	**1.81**	**5.57**	**0.17**	**5.72**	**0.21**	**0.05**	**0.00**	**6.71**	**163.69**
Conf. Level(95.0%)	1.17	5.88	0.18	0.43	0.74	0.13	0.75	0.15	0.07	0.00	0.82	4.04

Table 42: Correlation of Makhanga Observed and CSIRO Mk3.6 Model output

Variables	*ObMkJunTn*	*MKJunCSIRO*	*ObsMkNov*
MKJunCSIRO	0.034987	1	
ObsMkNov	**0.338067**	**0.349117**	1
MkCSIROTnNov	0.029717	0.212881	**0.311984**
obsTmaxNov	0.042429	0.219575	**0.565784**
ModelNovTmax	0.082069	-0.10843	0.150544
Mkobs_JunTmax	**0.37286**	0.194519	0.165092
MkModelJun	**-0.36716**	-0.02794	-0.14574

D Figures.

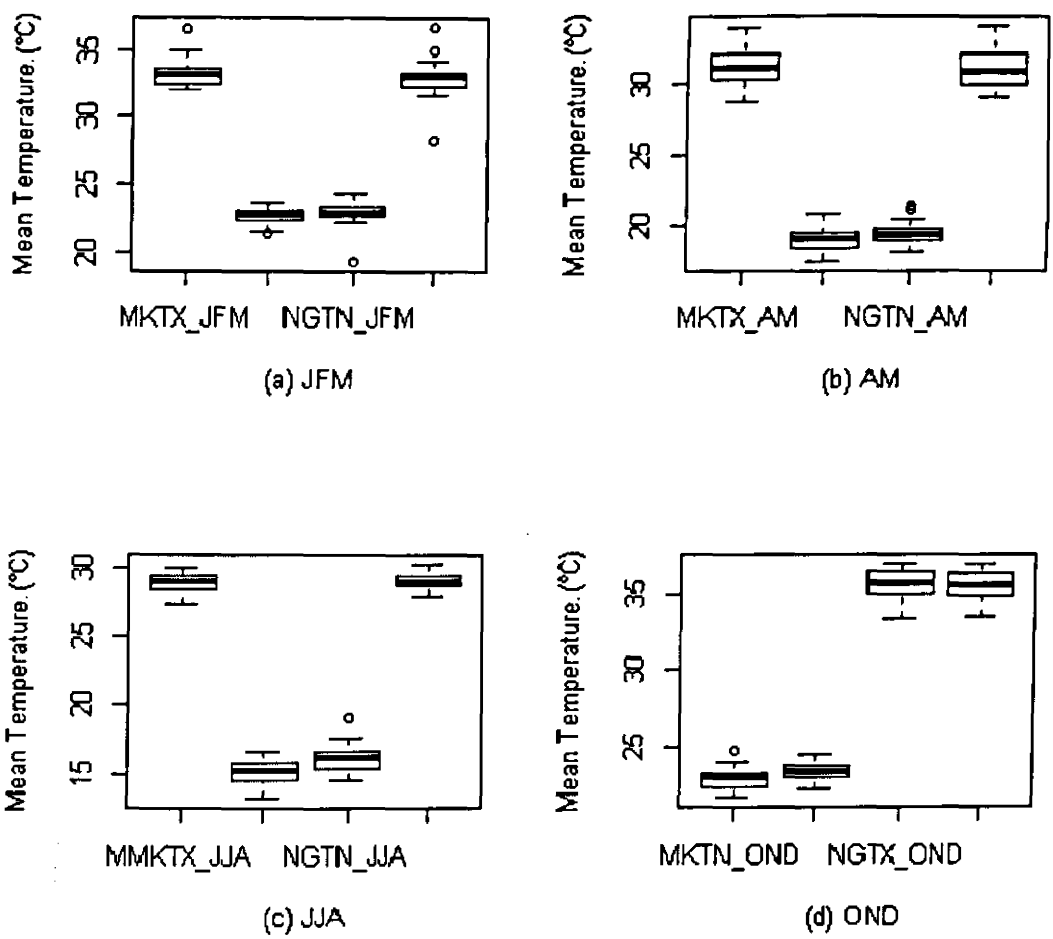

Figure 63: Boxplot showing variability of temperature in the Shire valley.

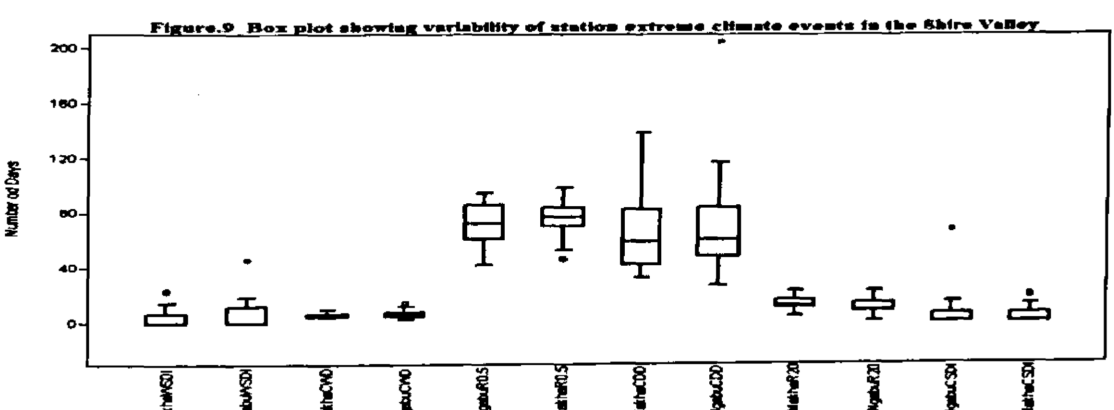

Figure 64: Box plot showing spatial variability of rainfall and temperatures extreme events for Makhanga and Ngabu.

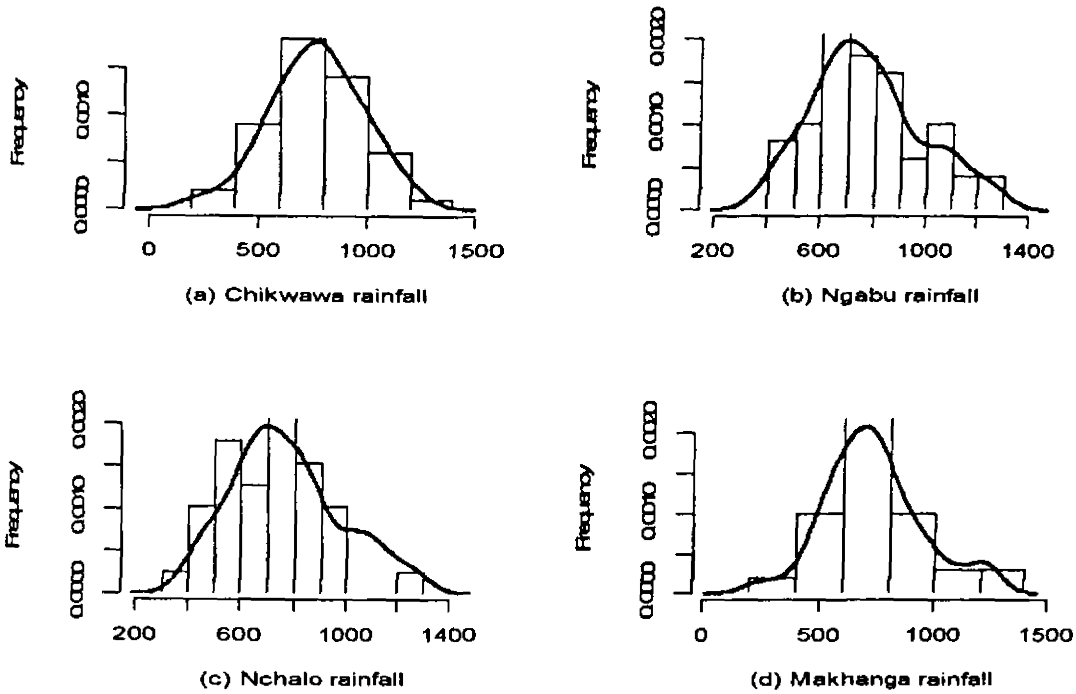

Figure 65: Shows frequency distribution of annual rainfall over Ngabu, Chikwawa, Nchalo and Makhanga

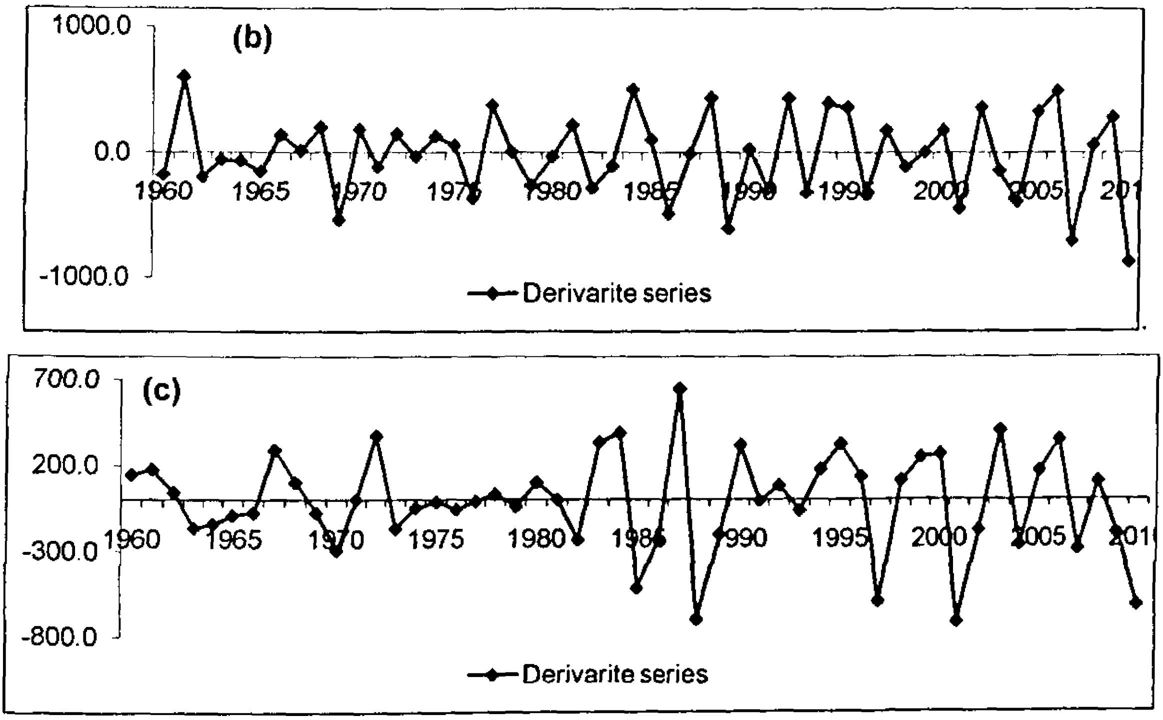

Figure 66:Shows derivative series for (b) Makhanga and (c) Chikwawa. A negative value indicates wet years and positive values indicates dry year. A wet year means a year with more rainfall than the previous year and vice versa.

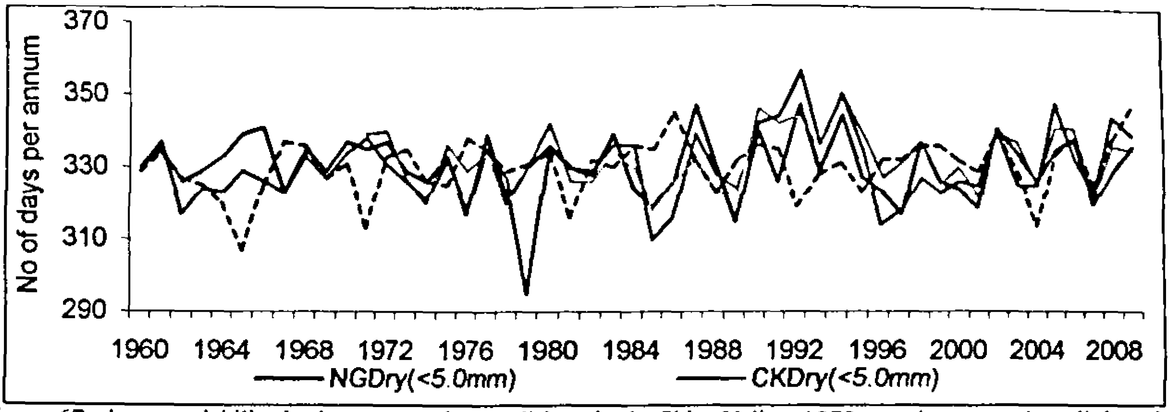

Figure 67: shows variability in the extreme dry conditions in the Shire Valley. 1978 was the wetter than all the other years while 1992 was the driest among the rest.

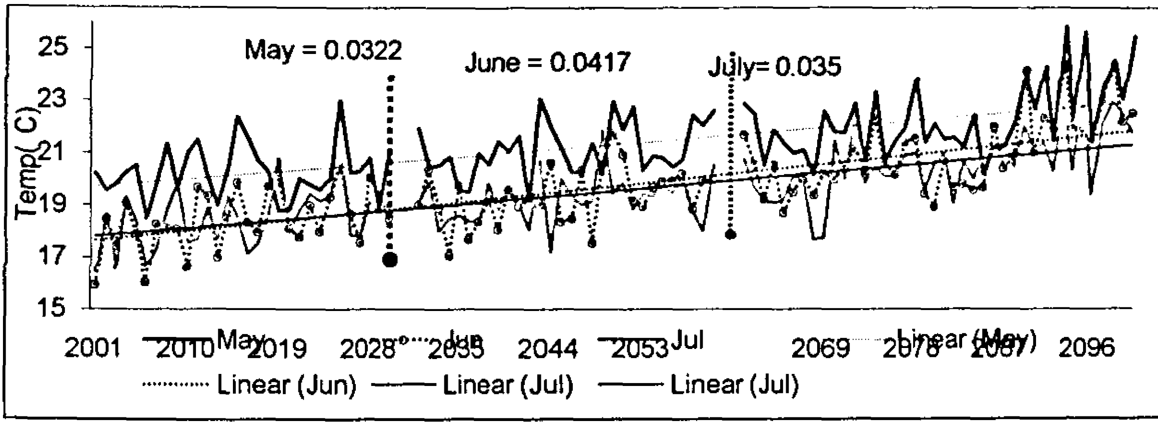

Figure 68:Figure.66: Shows variability of June, July and August monthly temperatures at Ngabu.

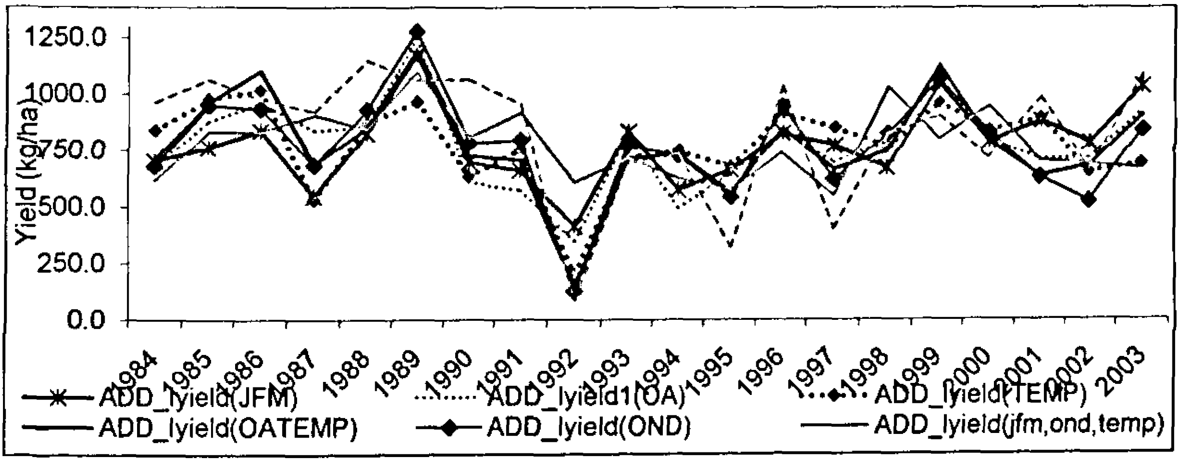

Figure 69: shows the difference of the effect of various combinations of climate variables on local variety sorghum yield. The R squares for the model used ranged between 0.26 to 0.66 and p_values ranging from 0.302 – 0.0407.

F APSIM SIMULATED YIELD

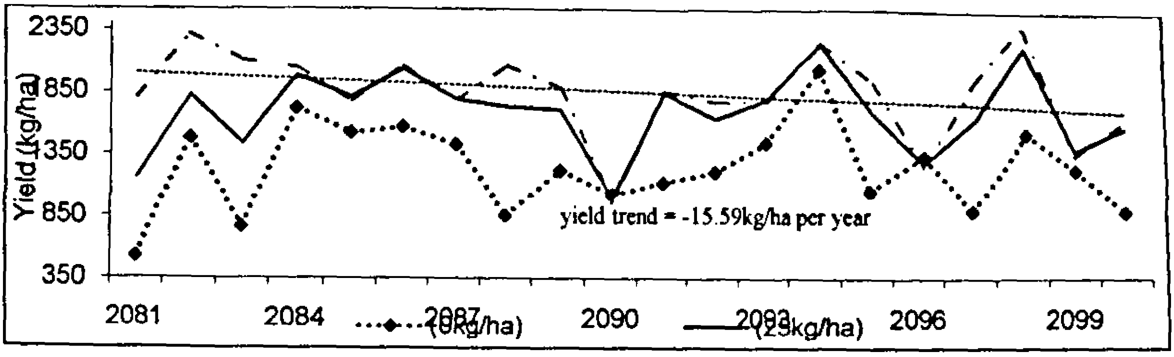

Figure 70: shows the effect of *(2080-2100)* change in temperatures over the *Shire Valley*.

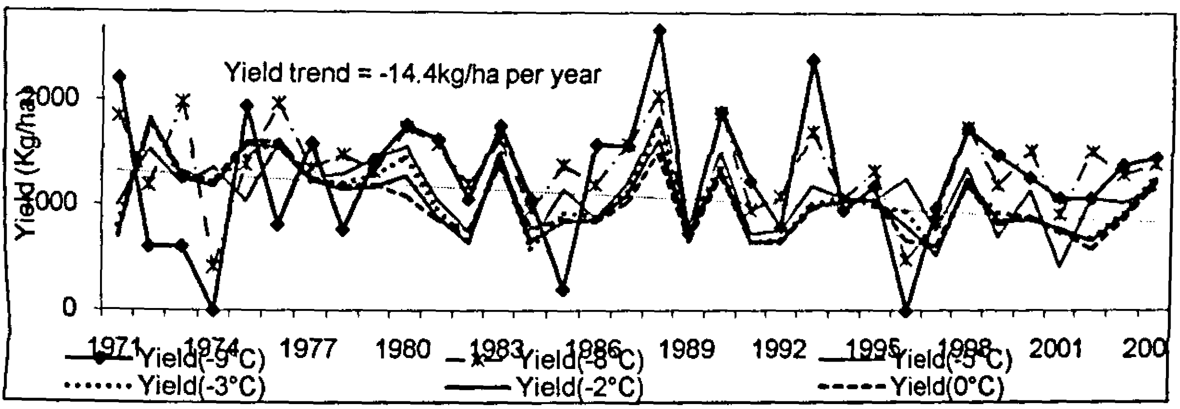

Figure 71: shows the effects of temperature on sorghum yield. A linear trend at 95% significance level shows yield decrease by about 14kg/ha.

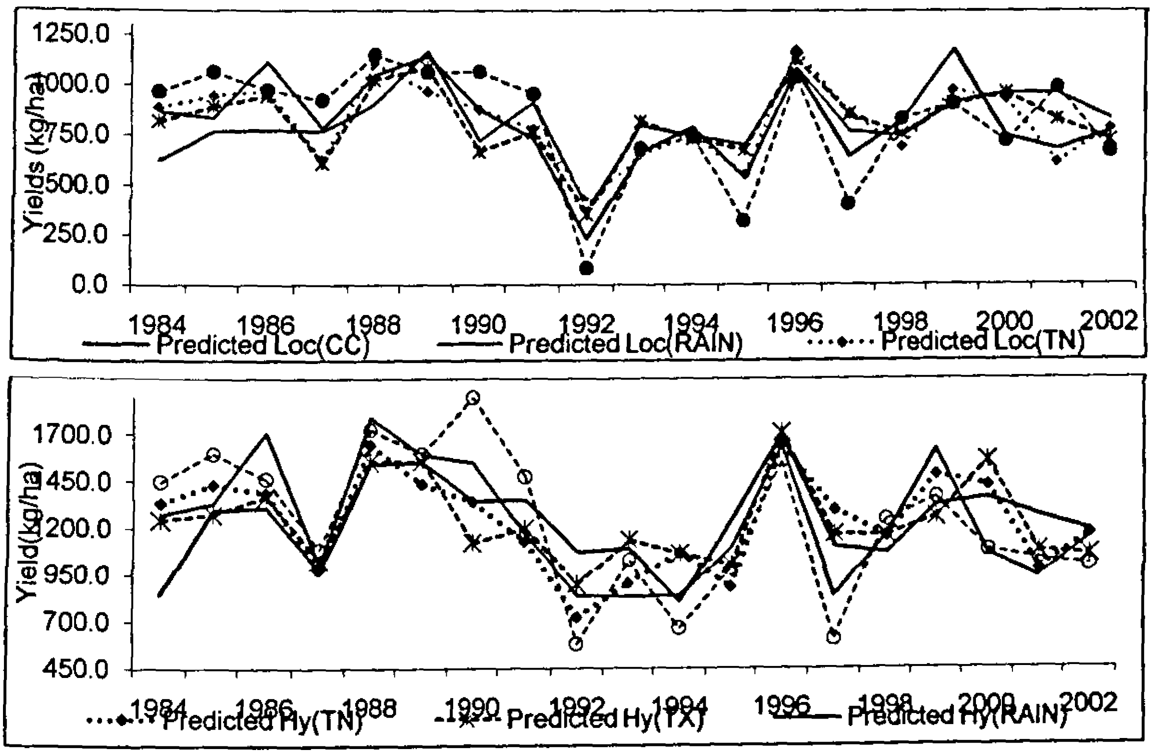

Figure 72: shows effect of Climate Change on sorghum yield for Hybrid and Local variety.