ASSESSING THE IMPACT OF CLIMATE VARIABILITY AND CHANGE ON SORGHUM YIELD OVER GADAREF AREA IN SUDAN

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DECLARATION

This project is my original work and has not been presented for a degree in this or any other university.

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DEDICATION

- My Mother:

Thank you for your unconditional support with my studies. I am Proud to have you as my mother. Thank you for giving me a chance to prove and improve myself through all my walks of life. I love you.

- My Family:

Thank you for believing in me; for allowing me to further my studies. Please don't ever doubt my dedication and love for you.

- My Brother:

Thanks for unlimited assistance along my studies period. Wish Allah give me health to serve and make you happy.

ABSTRACT

There is hardly any doubt that climate plays a significant role in shaping the face of the earth and in determining the type of economic activities that man may practice. The realization of the man climate relationship has led to growing interest in the science of climatology especially in the tropical areas where the controls exerted by the various climate factors, such as the annual rainfall and temperature, are really vital and effective.

The agriculture was considering the dominant sector in GDP of Sudan because by 1956 it accounted about 60% of the total GDP while whole the other sectors contributed about 40% of gross domestic production (Work Bank, 2003). Approximately 80% of the labor force of Sudan's population is employed in agriculture and related activities. Rain fed agriculture in Sudan is affected by drought and variation in seasonal rainfall amounts during the last decade and climate change impacts have been reported in many areas of the country. Gadaref area is considered one of the most important rain-fed agricultural areas in Sudan, and it contributes more than 40% of the rain-fed cereals produced in the country. The objective of this study is to assess the impact of climate variability and change on sorghum yield over Gadaref area in Sudan using AquaCrop model.

The trend analysis results show the maximum temperature and minimum temperature have significant trend (increasing trend) over the study area, implying that the temperature was been increasing over study area during the last decade. While the rainfall has an insignificant trend (decreasing trend) over the study area, indicating there was no significant change in rainfall during the last decade over the study area.

Maximum and minimum temperature showed a negative relationship with correlation coefficients of -0.34 and -0.31 with sorghum respectively. This implies that an increase in temperature beyond the optimum level (high temperature of about 26-30°C and low temperature of about 10-15°C) results in a decline in sorghum production and vice versa. On the other hand Correlation analysis showed a positive relationship between sorghum and rainfall (0.59) and sorghum and evapotranspiration (0.25). This means that an increase in rainfall enhances sorghum production; while its decrease results in poor sorghum yield.

Monthly results of coefficient of variation values indicated an increase in climate variability, which was shown by larger season to season fluctuations, with a higher coefficient of variation implying less predictability in the climate.

The result of analysis of multiple regressions showed a significant (30%) relationship between sorghum and the set of climatic factors used in study. It was observed that 30% of the variability in sorghum yield could be explained by these climatic factors (rainfall, maximum temperature, minimum temperature and evapotranspiration) and was significant at ($p=0.02$).

The impacts of changes in climate parameters; annual rainfall and temperature, was determined by using comparisons between the observed data (past and present) and projected data (Ncc Cordex Model).Climate variability results analysis revealed significant increase in minimum temperature of 11.2% (2.39 °C) by 2046, while rainfall was projected to decrease by 33% (202.46 mm) over Gadaref area during the same period.

The results of the study using AquaCrop model showed that by 2046, the Gadaref area's seasonal rainfall (June-September) decline by 233.6 mm (42%), would result in average sorghum yield decrease of 39.9%. while the seasonal temperature have significant impacts in sorghum yield, This is because there was projected increase in minimum and maximum temperature by 2.24°C (6.3%) and 2.48°C (10.2%) respectively. This implies that sorghum yield production will be very sensitive to reduction in rainfall and increase of temperature during the season over study area.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ANNEX TABLES

LIST OF ACRONYMS

CCCma	Canadian Centre for Climate Modeling and Analysis
CMIP5	Coupled Model Intercomparison Project Phase 5
CNRM	Centre National de Recherches Meteorologiques
CORDEX	Coordinated Regional climate Downscaling Experiment
CV	Coefficient of Variation
CVC	Climate Variability and Change
DI	Deficit irrigation
ETO	Reference Evapo-transpiration
FAO	Food Agricultural Organization
GCMs	Global Climate Models
GDP	Growth Domestic production
GFDL	Geophysical Fluid Dynamics Laboratory
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IFAD	International Fund for Agricultural Development
IPCC	Intergovernmental Program Climate Change
MAF	Ministry Of Agriculture and Forest
MIROC	Model for interdisciplinary research on climate
MK	Mann-Kendall
MLO	Mauna Loa Observatory
MOHC	Met Office Hadley Centre
MPI	Max Planck Institute for Meteorology
RMSE	Root Mean Sequare Error
NCC	Norwegian Climate Centre

NOAA	National Oceanic and Atmosphere Administration
RDI	Regulated Deficit Irrigation
RF	Rain Fed
SNHT	Standard Normal Homogeneity Test
SSA	Sub Saharan Africa
SSTs	Sea Surface Temperatures
Tmax	Maximum Temperature
Tmin	Minimum Temperature
UN	United Nation
UNDP	United Nation Development Program
UNFCCC	United Nations Framework convention on Climate Change
USGCRP	United States Global Change Research Program
WCRP	World Climate Research Program
WMO	World Meteorological Organization
WOFOST	World Food Studies
WP	Water Productivity

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background Information

There is hardly any doubt that climate plays a significant role in shaping the face of the earth and in determining the types of economic activities that human can practice. Realization of the human-climate relationships has led to a growing interest in the science of climatology especially in the tropical areas where the impacts exerted by the various climatic factors particularly rainfall and temperature are vital and effective. The African continent is particularly susceptible to climate change because it includes some of the world's poorest nations. Furthermore, high spatial and temporal variability in rainfall, as well as high evaporation rates, already place great stress on agricultural systems from which 70% of the continent's population derive their livelihoods.

The semi- arid and humid regions of the world may provide the best opportunity to increase the food production. Sorghum is one of the major crops, which are adapted to such climatic conditions. The semi-arid and humid regions are generally characterized by sufficiency precipitation to meet the evaporative demand of the atmosphere as well as by an uneven seasonal distribution of rainfall and a high year to year variability in other weather parameters. Sorghum is the world's fifth most important cereal after wheat, rice, maize, and barley in both production and area planted (FAO/ICRISAT, 1996). It is one of the main staples for the world's poorest and most food-insecure people (Henry and Kettlewell, 1996). The crop is generally suited to hot and dry areas where it is difficult to grow other food grains. These are also areas subject to frequent drought. In many of these areas, sorghum is truly a dual-purpose crop; both grain and Stover are highly valued outputs. In large parts of the developing world, Stover represents up to 50 percent of the total value of the crop, especially in drought years. Developing countries account for roughly 90 percent of the world's sorghum area, and generate 70 percent of total output (FAO/ICRISAT, 1996).

During the 1980s, poor rainfall contributed to low food production in Sudan. For example, a 10 percent decline in average rainfall levels induced a 5 percent drop in national cereal production. While sorghum production fell by 7 percent between the 1982 and 1987, millet yields dropped by only 3 percent. The 1984 severe drought for instance, caused a 92 % and 86 % decrease in sorghum and millet production respectively compared with production between 1974 and 1981 in Northern Kordofan (Teklu *et al*., 1991). Sudan is characterized by a wide range of climate variations, which vary from the desert in the northern parts of the country, where it seldom rains, through a southward belt of varying summer rainfall, to an almost equatorial type of rain in the extreme southwest, where the dry season is very short. These variations of climate are considered important features for the agricultural sector in Sudan.

Work bank reported on 2003 the agricultural sector alone in Sudan contributed by 45.6% of the GPD while the other sectors services and industry were contributed about 30.2% and 24.2% respectively. The agriculture is considering the dominant sector in GDP of Sudan because by 1956 it accounted about 60% of the total GDP. Agriculture also drives activities in the industry and service sectors such as transportation, agro-industries, and commerce, which account for a large part of the rest of the economy. 80% of the labor force of Sudan's population is employed in agricultural and related activities. Agricultural performance is the main determinant of year-to-year changes in poverty levels and the food security of the country, and it was the source of virtually all of the Sudan's exports before oil extraction. It is, therefore, a key determinant of the balance of payments.

Assessing the impact of climate variability on sorghum production in different parts of the world can be done through the use of crop and climate scenarios. Use of Climate Models helps in improving predictability of climate behavior on different time scales such as seasonal, annual, decadal, and centennial. Models help to examine the extent to which observed climate variability and change may occur as a result of natural variability, human activity, or both. Results and projections obtained from climate models provide important information that can be used to make informed decisions at national, regional, and local levels. These decisions include strategies that enhance water resource management, agricultural production and management, transportation, and urban planning among others. The Geophysical Fluid Dynamics Laboratory (GFDL) has played a key role in climate modeling and simulation for the past five decades.

The GFDL scientists in the early 1960s came up with the first coupled ocean-atmosphere general circulation climate model and they have been on the forefront in improving and making advancements in the world of climate modeling. The State-of-the-art climate modeling at GFDL was developed due to available vast computational resources including supercomputers with many processors and terabytes of data storage. Coordinated Regional climate Downscaling Experiment (CORDEX) is a World Climate Research Program (WCRP) -sponsored program to organize an international coordinated framework to produce an improved generation of regional climate change projections world-wide for input into impact and adaptation studies.

CORDEX produce multiple dynamical and statistical downscaling models considering multiple forcing global climate models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive. Initially 50 km grid spacing has been selected, favoring engagement of wider community. Multiple common domains covering all (or most) land areas in the World have been selected (with initial focus on Africa).

1.2 Problem Statement

Although Sudan lies within the tropics, its climate ranges from arid in the north to tropical wet in the far southwest. Climate factors such as temperature and precipitation have a critical influence on agriculture in Sudan. This has been justified by the increasing number of studies exploring changing trends of precipitation and temperature (Alvi, 1994; Alvi and Elagib, 1996; Ayoub, 1999; and Elagib, 2011).

The poor rainfall distribution that was recorded in the 1980s endangered the dependable supplies of sorghum and millet from rain-fed areas. This has seen the irrigated sorghum gain an increasing importance (Faki *et al.*, 1995).

The sorghum crop is sensitive to increase in temperature and decrease in rainfall. Although several studies have been undertaken to assess the general trends of temperature and rainfall over Sudan, there are no studies that have focused on specific areas that play key role in the country's economy. The Gadaref area that solely relies on sorghum has not been studied to understand how climate variability has affected sorghum yield over the last four decades. This study will, therefore, examine the variability of weather parameters over Gadaref area and assess their impacts on sorghum production in order to provide solutions to farmers on how to adopt climate smart agriculture

1.3 Objective of the Study

The main objective of this study is to assess the impact of climate variability and change on rain-fed sorghum yield over Gadaref area in Sudan. The specific objectives are;

(i). Determine the temporal variability and trend of climate parameters and sorghum yield over Gadaref area in Sudan.

(ii). Determine the relationship between the climate parameters and sorghum yield over Gadaref.

(iii). Assess the impact of future climate change on sorghum yield over Gadaref using the AquaCrop Model.

1.4 Hypothesis

This study has two null hypotheses; first is that there is no significant change in both temperature and rainfall, and the second hypothesis is that the expected future change in mean temperature and rainfall patterns, and variability of extreme events has no effect on the sorghum yield.

1.5 Justification

In Sudan, agriculture is one of the main pillars of the national economy. In the last years rain-fed agriculture has been affected significantly by climate variability and change, which may lead to reduction in agricultural productivity by reducing the suitable productive areas, increase in pathogens, or influence plant phenology used and the quantities produced. In normal weather conditions, the amount of cereal production especially sorghum and millet is usually sufficient for domestic needs (Faki *et al*., 1995).

The Gadaref region is known for production of sorghum, Sim Sim, and millet among other cereal crops. However, this area produces nearly 40% of the national sorghum production. Considering that the region is arid, it is important to understand how the rainfall varies in both quantity and temporal distribution. Since many studies have focused on climate change, there is need to assess the variability in climate and how these can impact the agricultural productivity (sorghum) of the study area. This study will provide the much needed climate information for short and long-term decision making strategies for sustainable development. It will also provide the basic climate information within Gadaref particularly for farmers who still highly depend on the traditional or indigenous knowledge in making decisions.

1.6 Area of Study

1.6.1 Location and Physical Features

The Gadaref state is located in eastern part of Sudan (Figure.1), bordered by Kassala state to the north, Khartoum to the northwest, Sinnar to the south, Gezira to the west and Eritrea to the east. The state covers a total area of 75,263 Km^2 (UN, 2003). It lies between latitude 12^o 45 N and 14^o 15 N and longitude 34^o E and 37^o E, its average altitude is 600 meters above sea level. This region is about 490 km from the capital Khartoum and 770 km from Port Sudan city; the main sea port of Sudan. Thus, the region’s geographical position is favorable for domestic and foreign trade (Ayoub, 1999). About one million people live in Gedaref area according to 1993 population census; ninety percent of them are classified as farmers engaged in settled agriculture, either in traditional or large scale mechanized farming, while the other 10% are engaged in semi-nomadic Pastoralism (Hassan Mustafa, Rajaa, 2006). The average population density of Gedaref area was estimated at approximately 13 persons per square kilometer.

The area is generally divided into three agro-ecological zones on the basis of the amount of rainfall and main agricultural characteristics. The northern zone with seasonal rainfall less than 500 mm; where animals especially sheep production is primarily practiced beside crop production, the central zone with rainfall range between 500 to 600 mm and the southern zone with rainfall range between 600 to 800 mm.

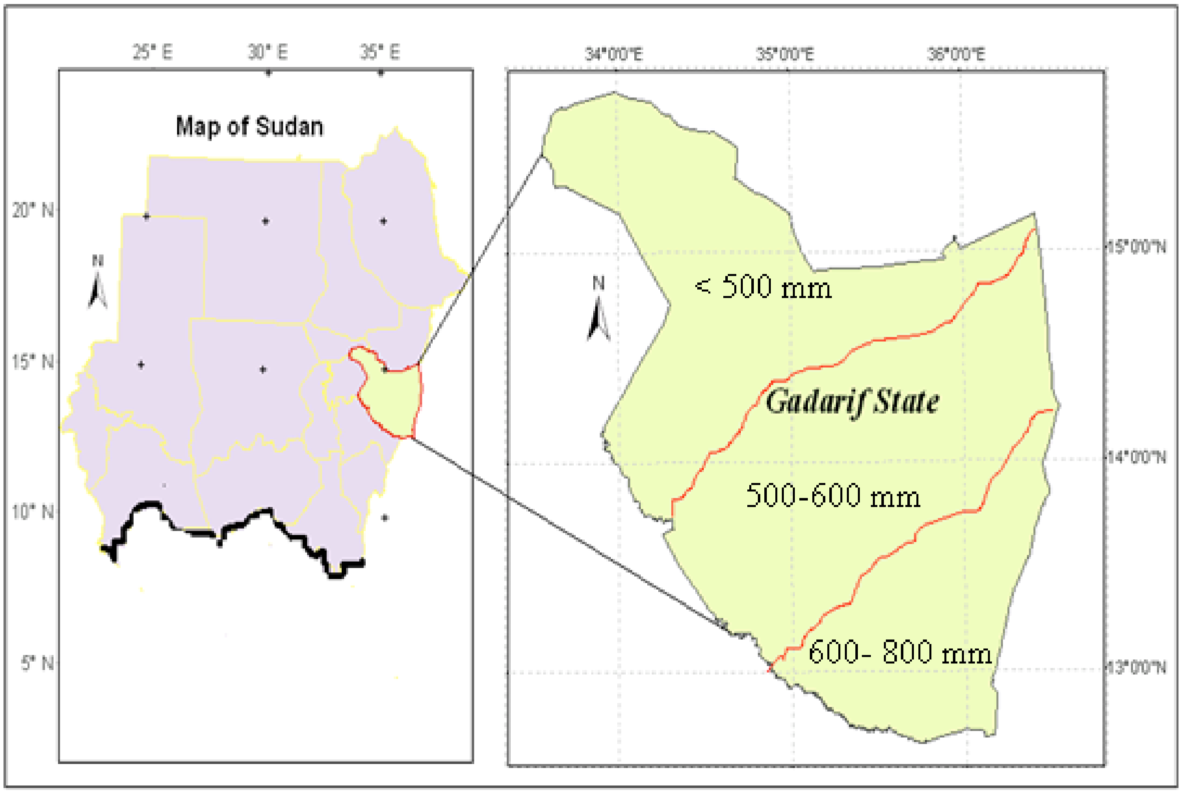

Figure 1: Map of Sudan Showing the Area of Study

(Source: Sudan Meteorological Authority, 2013).

1.6.2 *Climate*

The Gadaref region is characterized by semi-arid climatic conditions where rainfall is erratic and concentrated in only a few months of the year. The length of rainy season fluctuates around four months i.e. from June to September with the peak in August. The amount and distribution of rainfall in the study region vary greatly from 400 mm to over 700 mm with an annual average of 591 mm.

The highest amount of seasonal rainfall (750 mm) was received in 1999, followed by 1989 (725 mm); and the lowest amounts were recorded in 1984 and 1986 (442 and 408) respectively

(Rajaa, 2006). Although the total amount of precipitation during the rainy season may seem sufficient to meet the requirement of most crops, the high temperatures during the rainy months, together with a high percentage of light rainfalls events, substantially reduce the amount of effective rainfall.

1.6.3 Soils

The Gedaref area is characterized by a semi-arid climate, which is related to dark grayish brown soils with a high clay content of 75-80% and strong vitriolic properties. The organic matter and nitrogen content of the soil are low but as there is no deficiency of other plant nutrients, the soils are moderately fertile. The water holding capacity of the soil material is very high. This, in combination with the deep penetration of water in the soil through the vertisolic cracks, causes the available water holding capacity of the soil to be very high. This allows crops to grow on stored water during dry spells and long after the rainy season. The soils also have undesirable physical characteristics, such as a low permeability when wet, causing soils in water receiving sites to be waterlogged for certain periods during the rainy season. In addition, the soils are difficult to cultivate as they are very hard when dry and very sticky and plastic when wet, causing the moisture range at which the soils can be cultivated to be very narrow. Thus, mechanization of the land preparation operation is critical to work in this narrow time frame (Hassan Mustafa, Rajaa, 2006).

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Climate Change and Agriculture in Africa

Climate change resulting from increased concentrations of greenhouse gases in the atmosphere is expected to alter temperature and rainfall regimes worldwide. These changes accompanied with increased fluctuations, are predicted to cause a lot of decrease in crop water use and food production. Africa is expected to be more vulnerable to such a change where the current climate is already adverse with frequent droughts, high levels of poverty, rapid population growths, slow technological growth, and higher dependence of domestic economies on agriculture (Reid *et al*., 2007; Bates *et al*., 2008; Dinar *et al*., 2008). According to Cooper (2007), climate variability and change will have most profound impacts on agricultural production in the arid and semiarid areas in Africa.

According to UNDP (2011), 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). At the lower latitudes, especially the seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increase (1-2 °C), which would increase the food risk (Rai *et al*., 2010). Results from various studies have predicted that there will be an increase in the frequency and magnitude of extreme weather under climate change (Semenov, 2009; IPCC, 2007). Changes in climate variability and extremes have received increasing attention in recent years. Variability in the normally distributed parameter occur when changes in the mean, the variance, or both cause the probability distribution to shift, resulting in the changes in the frequency of occurrence of extreme events in either the upper or lower tail of the distributions.

Variability that is not well approximated by normal distributions is more complex especially for dry climates. Most of the earlier studies have associated climate variability to outcome such as yield, values, and farm economical profits (UNFCCC, 2007). Climate studies have focused on the yields and emphasized on the influence of the weather on the dynamic physiological process of plant growth and grain information. The studies also explored the use of theoretical models 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 climate change on various crops. By incorporating these scenarios into the crop models in some cases, the simulated yields compare to observed yields with remarkable success. For this reason, climate variability and change studies have become focal point of crop diversification around the globe (Mullera *et al*., 2011).

According to Mathews *et al*., (2007), most simulations indicate that sustained radiative forces following a doubling of CO_2 concentrations will increase global average surface temperature by between 2°C to 4.5°C, with a best estimate of about 3°C. Some Global Climate Models (GCM) simulate increased summer dryness and winter wetness over most parts of the globe including the Sub-Sahara Africa with a high chance of intense rains over Southern Africa due to greater water-holding capacity of a warmer atmosphere resulting into flooding (Knox *et al*., 2011). The IPCC (2007) also concludes that future tropical cyclones (typhoons and hurricanes) will likely become more intense, with peak wind speeds and more heavy rainfall associated with ongoing increases of tropical Sea Surface Temperatures (SSTs).

Climate variability negatively impacts crop production and inflict major on farming planning, especially under rain-fed conditions over the world. High growing season temperatures can significantly impact on the agricultural productivity, farm income, and food security (Battisti and Naylor, 2009). The moderate warming and more carbon dioxide in the atmosphere may help plants to grow faster (U.S. Census Bureau, 2011). Livestock may be at risk, both directly from heat stress and indirectly from the reduced quality of their food supply (N.J.Bello, 1997). Food and Agricultural Organization (FAO), the International Fund for Agricultural Development (IFAD), the World Bank and others acknowledge climate change as one of the challenges they need to address due to how it affect rural poverty. Although it is a global phenomenon, its negative impact is more severely felt by poor people in the developing countries who heavily rely on the natural resources for their livelihoods.

2.2 Sorghum Production in Africa

Sorghum is one of the most grown agricultural crops in Africa. This cereal is a source of livelihood for people living in the semi-arid tropics of Africa and Asia, which are too dry for other grain crops (FAO, 2009). Sorghum is one of the main staples for the world's poorest and most food-insecure people (Henry and Kettlewell, 1996). The crop is generally suited to hot and dry areas that subject to frequent droughts. These areas plant Sorghum for both grain and Stover, which represents up to 50 percent of the total value of the crop. Asia and Africa each account for about 25 and 30 percent of global sorghum production respectively, with Nigeria and Sudan being the major producers in Africa (Morgan and Finlayson, 2000). Sorghum production in Africa remains characterized by low productivity and extensive low-input cultivation. Generally, sorghum is grown primarily for food in the developing countries and animal feed in the developed countries. It is believed that Sorghum will remain a key food security crop in Africa for many decades.

In the competitive environment of multi-national enterprises, sorghum has been proven to be the best alternative to barley for liquor brewing. According to Dewalt (2002), the crop is only grown in specified part of the world, with other countries like the United States and Great Britain being importers of the cereal. Productivity gains are necessary to counterbalance the projection of continuing food production deficit in the most semiarid regions and prospects of famine that is observed periodically in some regions. Sorghum is still grown by the poorer small scale farmers, hence investments in research and extension is expected to help in alleviating poverty (Kleih *et al*., 2007).

Sudan grows more that 80% of its sorghum and millet under the rain-fed subsector (Faki *et al*., 1995). Throughout the country, sorghum is the major cereal crop and is considered the main pillar of food security providing about 60% of the quantity of the cereals consumed (Karim, 2002). Sorghum production between 1990 and 2001 in the mechanized rain-fed areas of the Gadaref represented 26% of the total production in Sudan. 45% of mechanized rain-fed sector gives information about the evolution of area, production, and yield of sorghum in the mechanized rain-fed agriculture of the Gadaref during the same period. The information reflects large variability in the area where the maximum area cultivated is 5.297 million feddans in the year 1997 and the minimum area grown is 1.826 million feddans in 1993 with an average of 3.435 million feddans and standard deviation of 0.933 million feddans during this period. This large variability in area is attributed mainly to the amount and distribution of rainfall. It is also influenced by the availability of credit and the prices of the previous season.

The production of sorghum in the Gadaref region reached its highest level of 1.215 million tons in the year 1999, while the lowest level of production of 0.183 million tons was recorded in 1991.The variation in the yield of sorghum reflects the present inadequate cultural practices and continuous cropping. In addition to weather conditions, yield is determined by the period of continuous cultivation, yield reaches its peak in the first two to four years then starts to decline until the seventh year where it stabilizes at the low.

2.3. Climate and soil requirements for sorghum

Sorghum tolerates a wide range of climatic and soil conditions. The climatic requirements for sorghum production are grouped to, rainfall, temperature, day length and water needs.

2.3.1. 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 that have an average annual rainfall of between 450 to 750 mm although it can respond well to soil moisture. It is the most tolerant crop to floods at all growth stages in terms 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 effect sorghum yield. It has been observed that the plant can absorb the moisture directly from the air and the rates of photosynthesis generally increase with relative humidity. This shows that in areas where the relative humidity is very low, crop yield is reduced due to poor photosynthetic process. Figure 2 shows sorghum crop growing under deficit rainfall conditions, while Figure 3 shows the crop under rain-fed conditions in Gadaref area.

Figure 2: Sorghum Crop Cultivation under deficit Conditions of Rainfall.

Source:https://www.google.com/search?q=image+for+sorghum+affected+by+high+temperature&biw=1600&bih=766&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwjX8uzluqHKAhXBWRQKHZfTAdoQsAQIHg&dpr=1#tbm=isch&q=image+for+sorghum+from+gadaref+in+sudan&imgrc=GE2NxHjHCjTmeM%3. **Accessed on 11/01/2016.**

Figure 3: Rain-fed Sorghum Crop Cultivation in Gadaref Area under Good Condition of Rainfall.

Source:https://www.google.com/search?q=image+for+sorghum+affected+by+high+temperature&biw=1600&bih=766&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwjX8uzluqHKAhXBWRQKHZfTAdoQsAQIHg&dpr=1. **Accessed on 11/01/2016.**

2.3.2. Temperature

Sorghum is a warm weather crop and requires high temperature of about 26-30°C for good germination and growth. Temperature plays a crucial role in its growth and development after germination. Minimum germination temperature varies from 7 to 10°C and at about 15°C, 80% of seeds germinate within 10 to 12 days (Patane *et al.*, 2009). Soil temperature strongly influences both percentage germination and time emergence of sorghum (Kanemasu *et al.*, 1975). The study further showed that sorghum needs optimum germination temperature of about 23°C and heat requirement of 67 degree days. Poor emergence and seedling growth may be seen if the crop is planted before a 35°C soil temperature is reached. This implies that the best time to plant is when there is significant water in the soil and the soil temperature is 15°C or higher at a depth of 10 cm. A temperature of 27°C to 30°C is required for optimum growth and development. Other studies have, however, showed that the temperature of as low as 21°C may not cause dramatic effect on the growth and crop yield (Fanrpan, 2010).

Low temperature rather than length of grown season is the limiting factor for the production (Carter, 1989). Exceptionally high temperature causes a decrease in the yield. Warmer air temperature accelerate plant phenology reducing dry matter accumulation and crop yields by 10 - 40% (Tubiello *et al*., 2006). Flower initiation and the development of flower primordial are delayed with increased day and night temperatures. High temperatures during the panicle stage leads to reduction in the grain yield of sorghum as a result of shortened panicle development period (Peacock and Wilson, 1984). Sorghum performs poorly in cool soil conditions especially during its early growth stage since temperatures below freezing are detrimental and may kill the plant. At 1 to 3 weeks from germination the plants may recover if exposed to a temperature of 5°C below freezing point, but at 7°C below freezing, the plants are killed. Frost will generally destroy the top parts of the plant and lower the moisture content (Carter *et al.*, 1989). Plants older than three weeks are less tolerant to low temperatures and may die off at 0°C. Downes (1972) in his study found that air temperature >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.

2.3.3. Day length

Sorghum is one of the most photosynthetically efficient plants with the highest dry matter accumulation rates. It is the fastest maturing food plants (Borlaug *et al*., 1995). Sorghum is a short-day plant, which implies that it requires short days/long nights before proceeding to the productive stage. It is more sensitive to photoperiod during the flower initiation. The optimum photoperiod for inducing the flower formation is between 10 to 11 hours and beyond these hours the vegetative growth is stimulated.The tropical varieties are usually more sensitive to the photoperiod than the quick, short season varieties. The rate of the growth is largely determined by the net photosynthetic rate of the leaves and panicle. Escalada and Plucknett (1975b) in their study found that the sorghum matures early with higher temperature and shorter day length. They 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 lead to low grain yields.

2.3.4. Water requirements

Sorghum is cultivated in Gadaref area on a wide range of soils under varied rainfall conditions of approximately 500 mm in the northern zones, 500 to 600 mm in the central zones and 600-800 mm in the southern zones. Crop water required basically depends on the climate such that a crop requires more water in a hot and sunny climate per day compared to a cool and cloudy climate. This is because the crop needs to make a balance between the water evaporated and that used in the other plant processes. Sorghum crop growth stages are critical to water stress and fully grown crops require more water compared to just grown crops (FAO, 2009). The water required for sorghum under moisture stress according to FAO is that between 90 to 140 days, the crop requires between 50 – 650 mm per growing period of water.

2.3.5 Soil requirements

Sorghum is mainly grown on low potential, shallow soils with high clay content, which usually are not suitable for the production of maize. Sorghum usually grows poorly on sandy soils, except where heavy textured subsoil is present. Sorghum is more tolerant of alkaline salts than other grain crops and can therefore be successfully cultivated on soils with a pH (KCl) between

5,5 and 8,5. Sorghum can better tolerate short periods of waterlogging compared to maize. Soils with a clay percentage of between 10 and 30 % are optimal for sorghum production (Jean Du, 2008)

2.4. Modeling Crop Production

A crop water productivity model AquaCrop was developed by the Land and Water Division of FAO and released for use in 2009 (Steduto *et al.*, 2009; Raes *et al.*, 2009). AquaCrop is a water-driven crop model to simulate yield response of several herbaceous crops to water. It is designed to balance simplicity, accuracy and robustness, and is particularly suited to address conditions where water is a key limiting factor in crop production(Akbarzadeh and Hrymak, 20016). Parameterization and validation of the AquaCrop model has been done to help simulate maize yield response to water (Hsiao *et al.* 2009; Heng *et al.* 2009). Although AquaCrop is based on complex crop physiological processes, it uses a relatively small number of explicit and mostly intuitive parameters with simplicity and accuracy (Steduto *et al.*, 2009; Raes *et al.*, 2009). Some of the advantages of AquaCrop include its wide applicability with acceptable accuracy, use of commonly available input (climate, soil, crop, and field data) and easy verification of simulation results with simple field observations.

In an attempt to compare performance of AquaCrop, CropSyst, and WOFOST Models, Todorovic *et al.* (2009) simulated sunflower (*Helianthus annuus L.*) growth under different regimes of water in a Mediterranean setting. The differences among the three models are in the complexity level used to describe the development of the crop in the main growth module that undertakes the simulation of the growth of biomass as well as the number of parameters that are incorporated to achieve the results. AquaCrop is completely based on the water-driven growth module. This module involves the conversion of transpiration into biomass by using water productivity (WP) parameter. On the other hand, the CropSyst model is based on both water and radiation driven modules. The WOFOST uses a fraction of received radiation and a carbon driven approach to simulate crop growth. The crop models were validated on a full irrigation treatment in 2005, and various deficit irrigation (DI) treatments such as regulated deficit irrigation (RDI) and rain-fed (RF) conditions. It was later calibrated using data obtained from a full irrigation treatment in 2007.

Although it was observed that AquaCrop needed less input information compared to CropSyst and WOFOST, it produced similar results in simulating both crop yield and biomass. The use of minimal data input and water-driven crop growth module of AquaCrop resulted in simulated yield in line with the data intensive and radiation driven CropSyst and WOFOST models. Therefore, it can be recommended that under conditions of limited input information and yield predictions under variable water supply situations, researchers should prefer to use the AquaCrop model and simpler models over other complex models. Figure 4 shows the flow chart of the AquaCrop model, showing the functional relationships between the different model components.

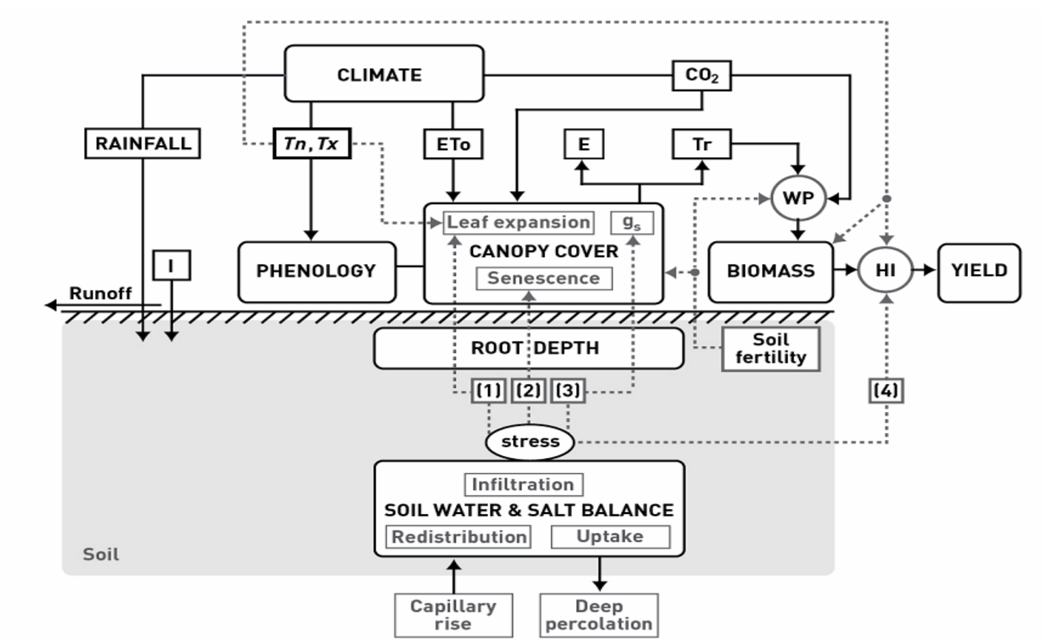

Figure 4: AquaCrop Model flow chart and the relationship between the model components.

CHAPTER THREE

3.0 DATA AND METHODOLOGY

This chapter gives the details of the type, sources, and the duration of the data as well as the methodologies that were used to achieve the specific objectives of this study.

3.1 Data

3.1.1 Climate data

The climate data that were used in this study are monthly maximum and minimum temperature, rainfall (1961-2014), and Evapotranspiration (1961-2007) for agro-meteorological station in Gedaref area. These datasets were obtained from Sudan meteorological Authority. Carbon dioxide concentration data were retrieved from the FAO manual, Mauna Loa Observatory (MLO).

3.1.2 Crop data

The crop data used include the type of crop (sorghum), phenological stages (emergence, flowering, maturity, harvesting) and length of growth cycle; these data were obtained from Ministry of Agriculture and Forest (MAF) in Sudan (Annex 1).

3.1.3 Soil data

The soil data included the soil type, root depth, soil texture and water balance. These data sets were obtained from Ministry of Agriculture and Forest and Food Agricultural Organization manual (Annex 2).

3.1.4 Management data

In the Gadaref area the method of planning as practiced by farmers is not documented. Therefore, used default values of management input data in AquaCrop is in relation to rain-fed, fertilizer application and use of lands (Annex 3).

3.2 Methodology

3.2.1 Estimation of Missing Data and Quality Control

There are several methods to estimate missing weather data. The chosen method depends on the nature of the missing data (temporal or spatial). This study employed correlation and arithmetic mean method because of the few missing data among whole the data sets used; the formula is shown in Equation 1.

$$x_i = x_o \frac{\overline{x_i}}{\overline{x_o}} \quad \text{.......................................} \ \mathbf{(1)}$$

Where X_i is the estimated data

X_o is the data of the station with highest correlation with station whose data is missing, while

$\overline{x_o}$ represents the mean value for the station with complete data.

$\overline{x_i}$ Is the mean value for the station with missing data.

The consistency of the rainfall, temperature and the sorghum yield data were tested by using the Standard Normal Homogeneity Test (SNHT).

The SNHT test (Standard Normal Homogeneity Test) was developed by Alexanderson (1986) to detect a change in a series of rainfall data. The test is applied to a series of ratios that compare the observations of a measuring station with the average of several stations. The SNHT works by calculating the mean of the data on the previous period and on the following period. The test statistic at each observation is then computed as described in Haimberger (2007). Essentially, though, it just compares the means of these two periods and normalizes by the standard deviation.

3.2.2 Determining the Trend and Variability of Climate Parameters and Sorghum Yield

The statistical techniques used for trend analysis can be either parametric or non-parametric. For parametric method, the coefficient of variation is used to check the variability of climate parameters while the Mann Kendall test was used to determining the trend of climate parameters for non-parametric method. The coefficient of variation and the Mann Kendall techniques are discussed in the next sub-section.

3.2.2.1 Mann Kendall Test

The Mann-Kendall (MK) test helps to statistically assess if there is a monotonic upward or downward trend of the variable of interest over time (Kendall, 1975). A monotonic upward (downward) trend implies that the variable constantly increases (decreases) with either a linear or nonlinear trend. Hirsch, et .L., (1982) pointed out that the MK test is best viewed as an exploratory analysis and is mostly used to identify stations where changes are significant or of large magnitude and to quantify these findings.

$$\mathbf{S} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathbf{sgn}(\mathbf{X_j} - \mathbf{X_i}) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .. (\mathbf{2})$$

Where X_i and X_j are sequential data values and n is the length of data, which is the number of positive differences minus the number of negative differences. If S is a positive number, observations obtained later in time tend to be larger than observations made earlier. If S is a negative number, then observations made later in time tend to be smaller than observations made earlier.

3.2.2.2 Coefficient of Variation

Coefficient of variation (CV) was used for determining variability in rainfall and temperature was applied to meteorological data. The coefficient of variation (CV) is a statistical measure of how the individual data points vary about the mean value (Trenberth, 1984). CV is calculated by dividing the standard deviation by mean. 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 (CV %) = (**Standard Deviation** / **Mean**) x100……. ……………….(3)

3.2.3 Determining the Relationship between the Weather Parameters and Sorghum Yield

To determine the relationship between climate data and sorghum yield production, there are several statistics tools or techniques, which can be used but this study adopted correlation and regression techniques. Focus was made on annual data (1970-2007) to understand how the events impact on sorghum yields.

3.2.3.1Correlation Analysis

This method provides the degree of relationship between two variables. The Pearson correlation coefficient r is a measure of the linear relationship between two attributes or columns of data. The value of (r) range from -1 to +1 and is independent of the units of measurement. The value of r near 0 indicates little correlation between attributes, a value near +1 or -1 indicates a high level of correlation. For this study, the value of r was calculated using the Pearson correlation coefficient equation

$$r = \frac{\sum_{i-1}^{N} (X_i - \overline{X})(Y_i - \overline{Y})}{\left[\sum_{i-1}^{N} (X_i - \overline{X})^2 \sum_{i-1}^{N} (Y_i - \overline{Y})^2 \right]^{1/2}}$$

……………………… (4)

Where **r** is correlation coefficient, X is independent variable and represents the Temperature, Rainfall and Evapotranspiration. Y is dependent variable and represents the sorghum yield. $\overline{X}$ and $\overline{Y}$ are the mean of independent variables and dependent respectively. i=1, 2, 3,…., N where N is number of variables.

To test the significance of the correlation coefficients obtained, student t test as shown in Equation 5 was used. Where r is the correlation coefficient and n is the total number of data points.

$$t = r\sqrt{\frac{n-2}{1-r^2}} \quad \text{...} \quad \textbf{(5)}$$

Where:

t is the absolute student t-statistic

r is the correlation coefficient

n is sample size

n-2 is degree of freedom

3.2.3.2 Multiple Regression Analysis

Multiple regressions are an extension of simple linear regression in which more than one independent variables (X) are used to predict a single dependent variable (Y). The predicted value of Y is a linear transformation of the X variables such that the sum of squared deviations of the observed and predicted Y is a minimum.

With n independent variables, the prediction of Y_n is expressed by Equation 6:

$$\mathbf{Y_n = b_0 + b_1X_1 + b_2X_{2...}+b_n X_n} \quad \text{...} \quad \textbf{(6)}$$

Where Y is the dependent variable b_0 is an intercept, b is coefficient of independent variables X and n refers to the n^{th} observation.

3.2.4 Assessing impacts of Climate Variability and Change on Sorghum Yield

To assess the impact of climate variability and change on the sorghum yield, the AquaCrop model was used.The AquaCrop Model utilizes rainfall, temperature, reference evapotranspiration and carbon dioxide concentration as the input data. The combinations of these variables were used to make climate files for the base year and the years under climate variability.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

This chapter provides the results obtained from all the analyses carried out to meet the specific objectives of this study. The results are presented sequentially according to the specific objectives.

4.1 Data Quality Control

4.1.1 Estimation of the Missing Data

The climatic data (rainfall and temperature (maximum and minimum)) of Gadaref meteorological station was available from (1961-2014), evapotranspiration from 1961 to 2007. While the sorghum yield data was available for 42 years starting from 1970. Gadaref station had 6 % missing data which were estimated using the arithmetic mean method.

4.1.2 Test for Data Homogeneity

Figures 5 to 8 show the homogeneity test results, in which standard normal homogeneity test (SNHT) of rainfall, maximum temperature, minimum temperature and evapotranspiration for the Gadaref station were plotted against time. The plotted time series for rainfall indicated homogeneity for selected years from 1963 to 2006 (Figure 5) since the shift or break of the mean find outside the range for all climate parameters for Gadaref station. Maximum temperature was found to be homogeneous from 1963 to 2011 (Figure 6) and minimum temperature was homogeneous from 1963 to 2008 (Figure7). The SNHT for evapotranspiration shows homogeneity for years from 1964 to 2005 (Figure 8). This implies that the data sets for the above climatic parameters, which were used in the study, were homogeneous. The nonhomogeneous shown in the figures is after and before the period selected for study (1971-2000). The climate data used in study is for period from 1971 to 2000 because the sorghum data was available from 1971 up to 2000.

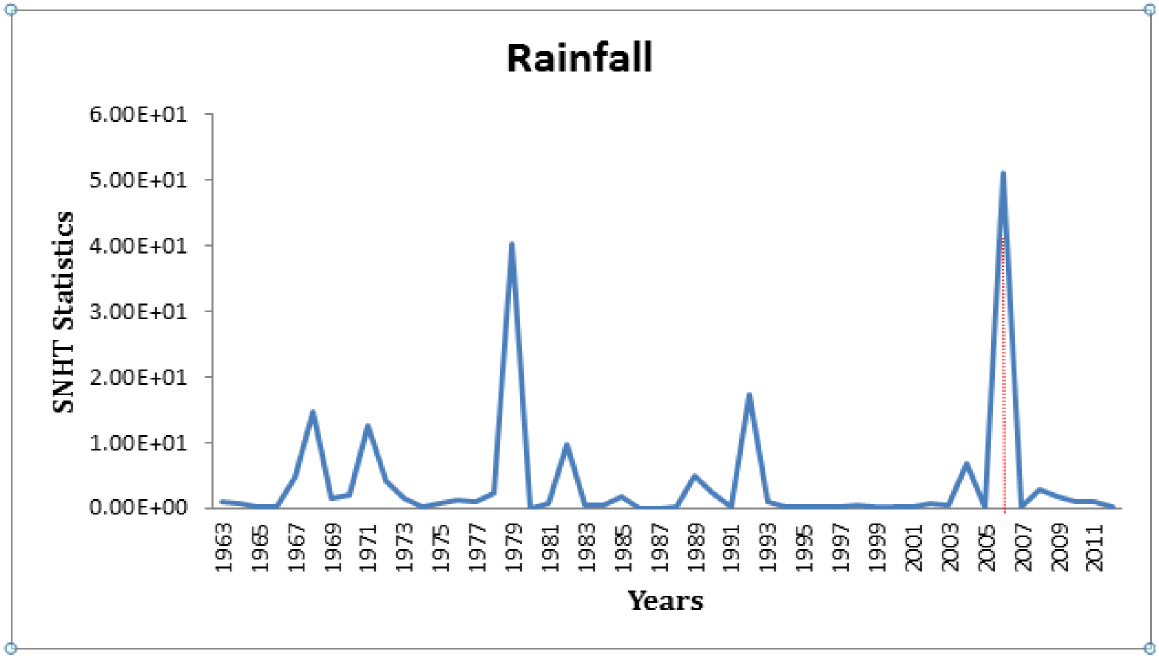

Figure 5: Standard normal homogeneity test of rainfall for Gadaref area from 1963 to 2014.

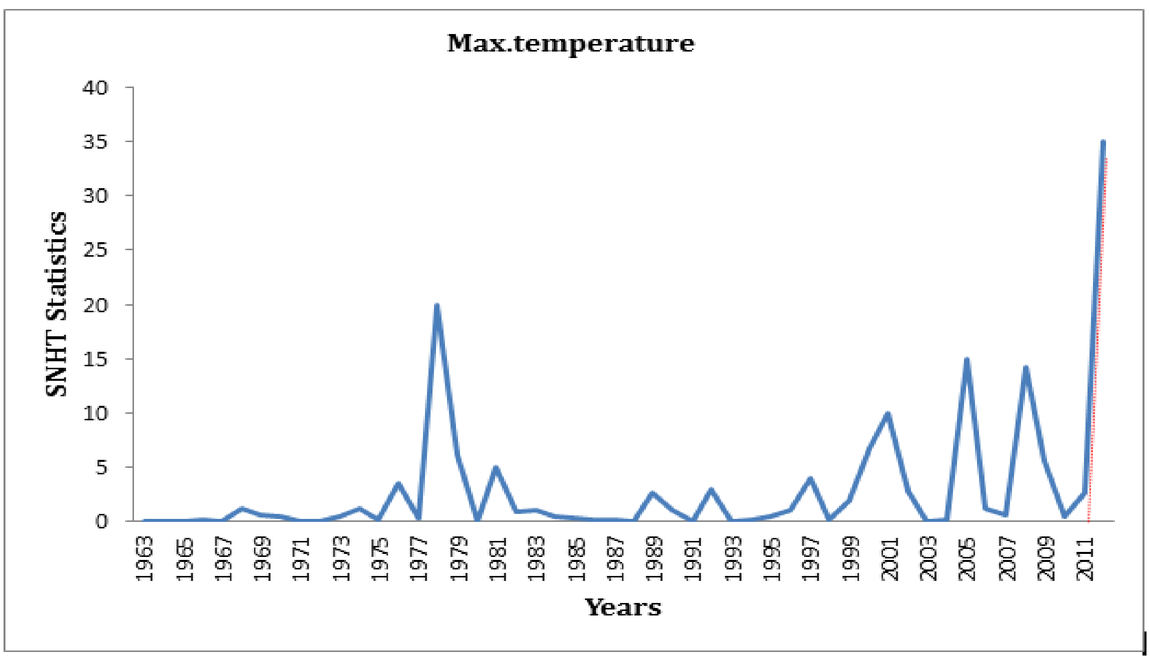

Figure 6: Standard normal homogeneity test of average maximum temperature for Gadaref area from1963 to 2011.

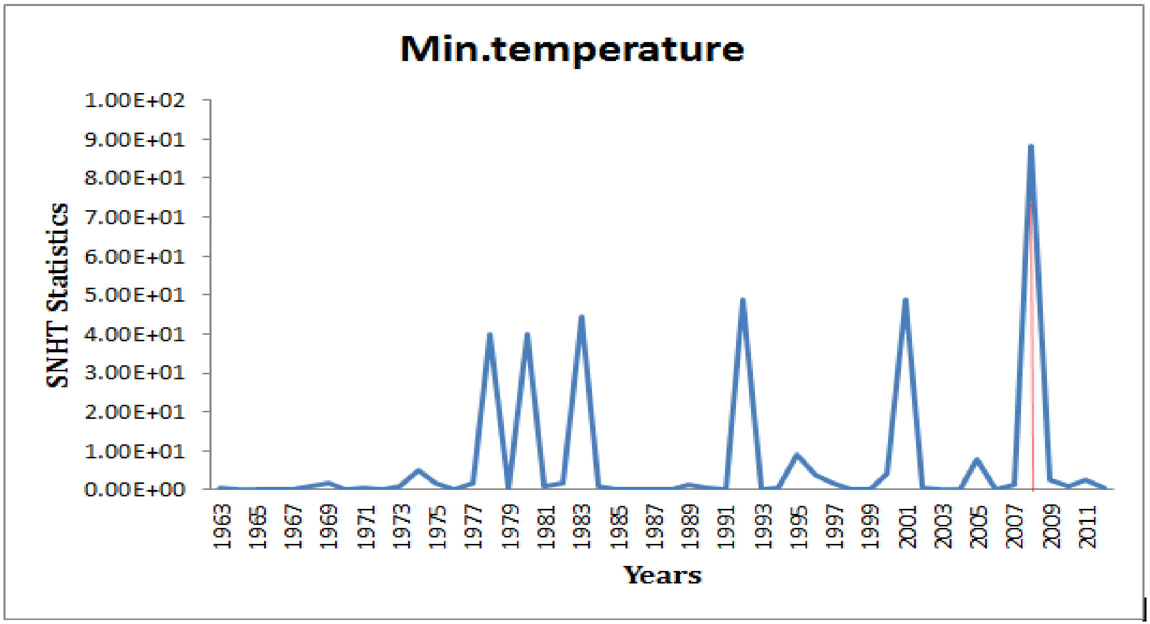

Figure 7: Standard normal homogeneity test of average minimum temperature for Gadaref area from 1963 to 2014.

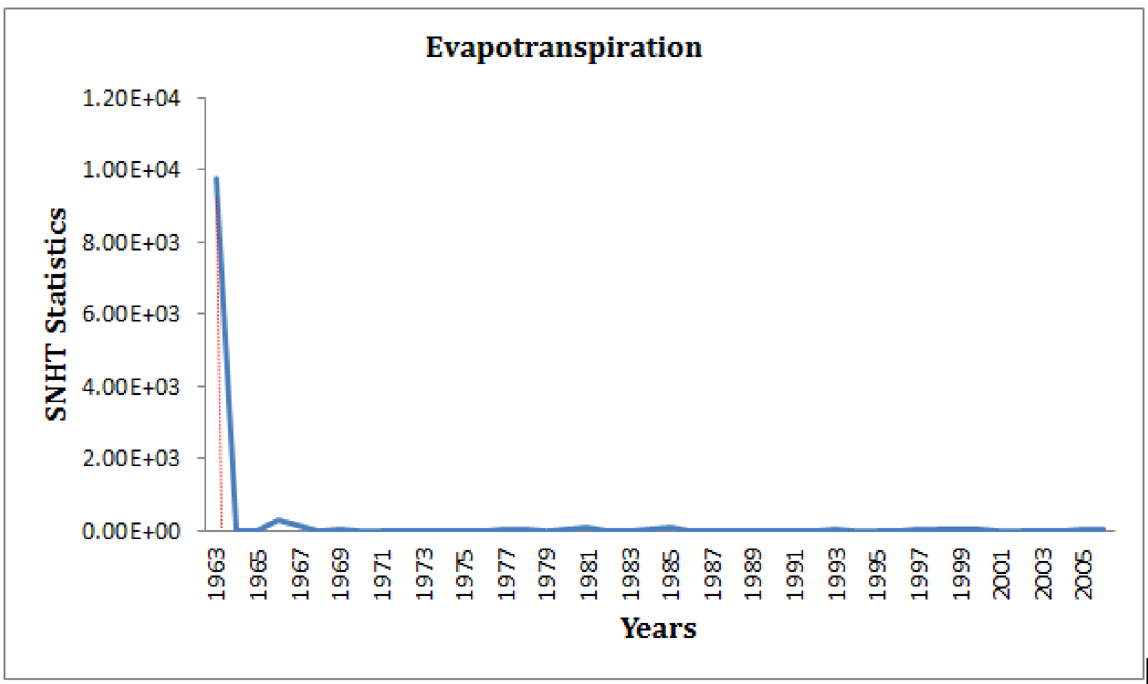

Figure 8: Standard normal homogeneity test of evapotranspiration for Gadaref area from 1963 to 2007.

4.2 Variability of Climate Parameters and Soghum Yield

4.2.1 Trend analysis

The Mann Kendall trend analysis was carried out for sorghum yield and climatic parameters such as the maximum temperature, minimum temperature, rainfall from and evapotranspiration. Results showed that, sorghum (Figure 9) and rainfall (Figures 10) have an insignificant trend, because of p.value for rainfall and sorghum almost egual or close to one (0.98 and 0.51) respectively . On the other hand, it was showed a significant, increasing trend for maximum temperature (Figure 11), minimum temperature (Figure 12), evapotranspiration (Figure 13) (the p.values were 0.000131, 0.000562 and 0.000176 respectively) was observed.

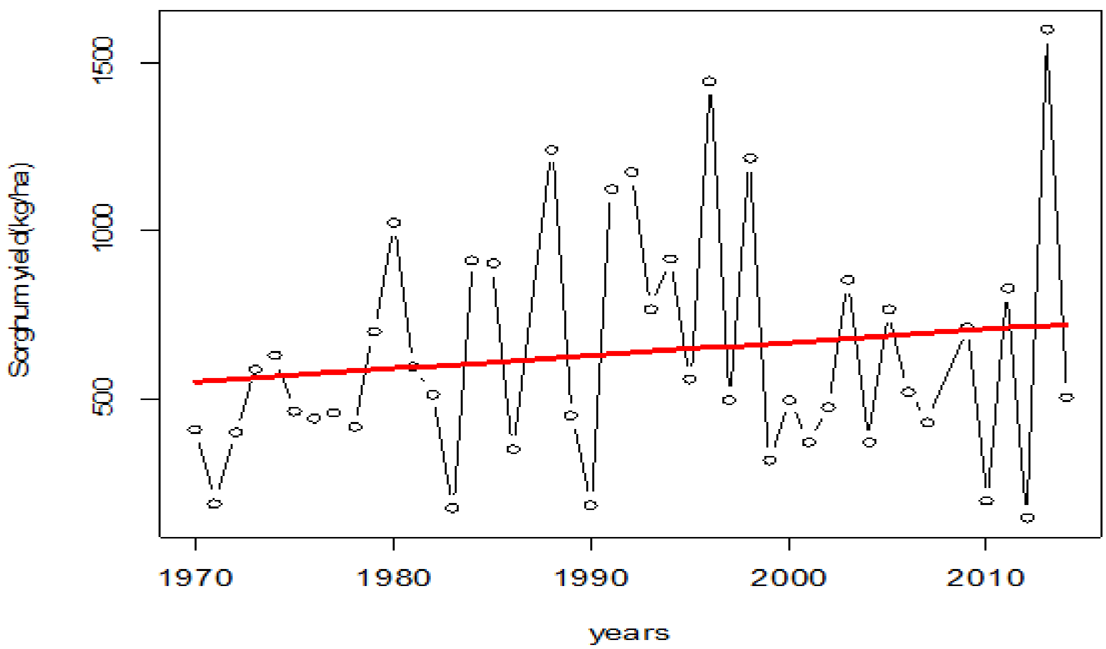

Figure 9: Mann Kendall Trend Analysis of Sorghum Yield for Gadaref Area from 1970 to 2012.

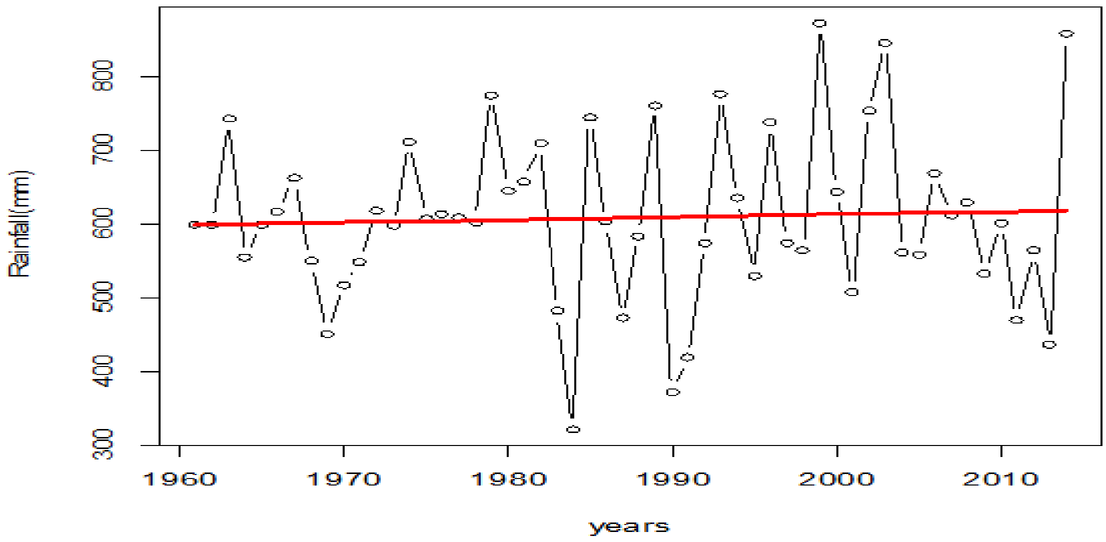

Figure 10: Mann Kendall Trend Analysis of Annual Rainfall for Gadaref Area from 1960 to 2014.

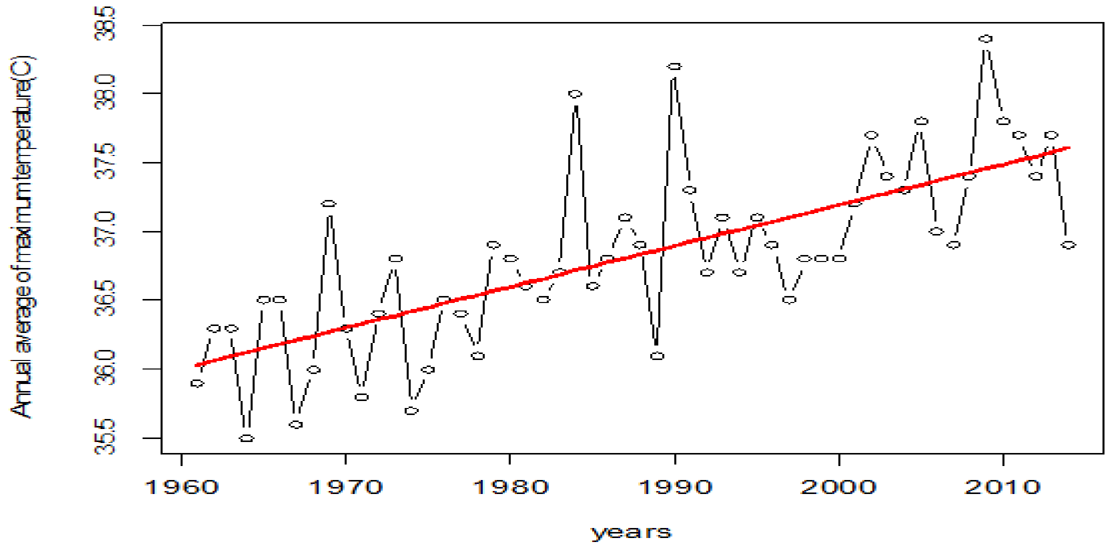

Figure 11: Mann Kendall Trend Analysis of Annual Average of Maximum Temperature for Gadaref Area from 1960 to 2014.

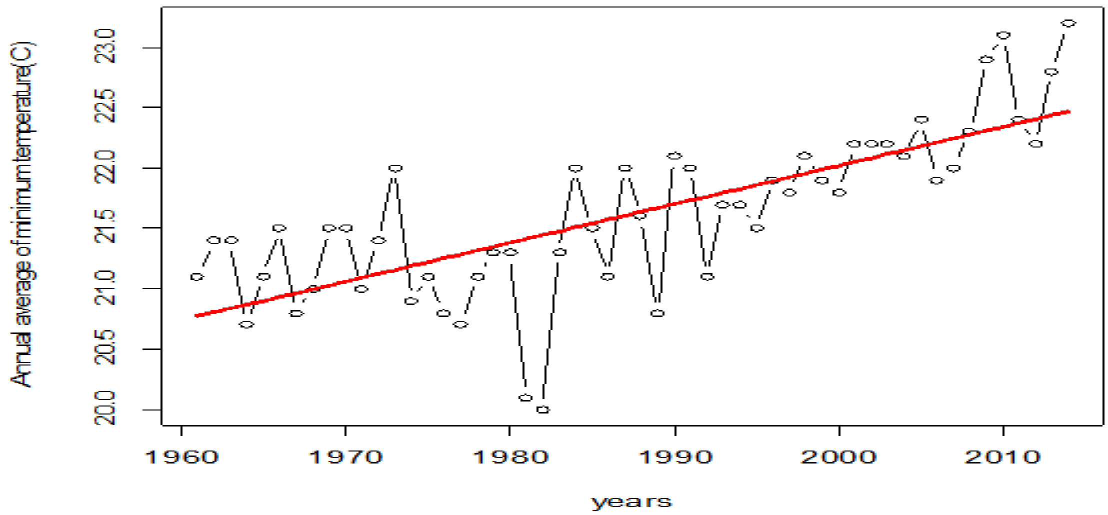

Figure 12: Mann Kendall Trend Analysis of Annual Average Minimum Temperature for Gadaref Area from 1960 to 2014.

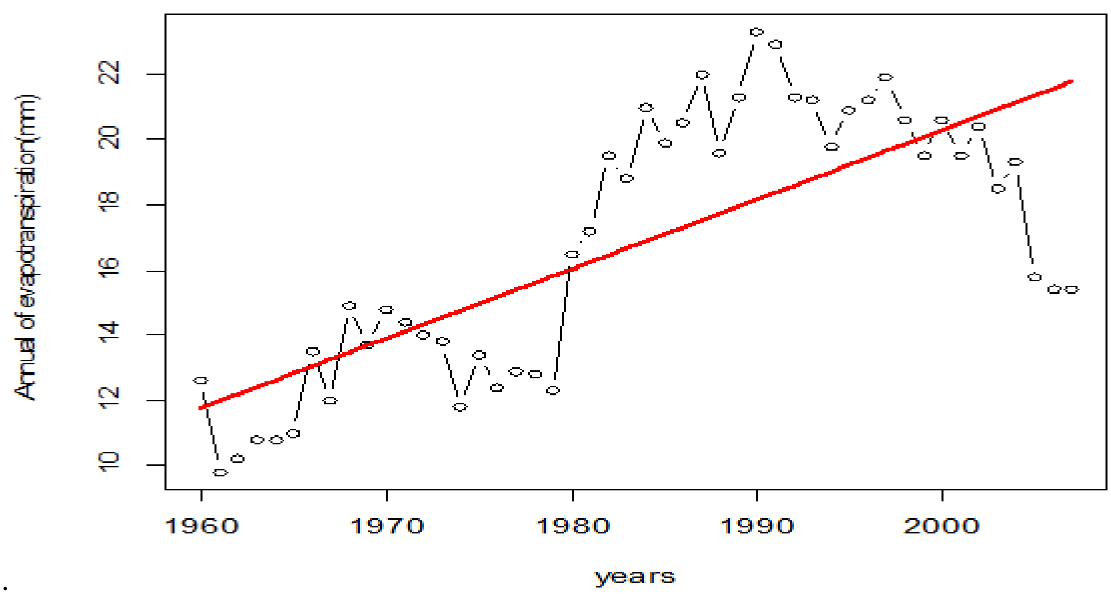

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Figure 13: Mann Kendall Trend Analysis of Annual Average Evapotranspiration for Gadaref Area from 1960 to 2014.

From the results above, it can be observed that there has been a continuous increase in maximum, minimum temperature and evapotranspiration over the study area. The increase in temperature can be interpreted as evidence of temperature rise that is being currently recorded in many parts of the world as scientist prove the reality of climate change. On the other hand, rainfall and sorghum yield depict an insignificant increase over the last five decades over the study area.

4.2.2 Analysis of coefficient of variation of climate parameters

Coefficient of variation (CV) was used to explain climate factors variability in Gadaref area. Higher value of CV indicated a greater degree of climate factors variability from year to year.

Monthly coefficient of variation values are as shown in Tables 1.Increase in climate variability was shown by larger season to season fluctuations, with a higher coefficient of variation that implying less predictability in the climate.

Table 1: Coefficient of Variation of Minimum and Maximum Temperature, Evapotranspiration and Rainfall for Gadaref Area.

Tmax is Maximum Temperature, **Tmin** is Minimum Temperature, **Eva** is Evapotranspiration and **Rain** is Rainfall**.**

CV% of	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{max}	3.2	4.3	2.5	2.5	2.8	4.4	4.0	3.7	3.2	2.8	2.4	3.1
T_{min}	9.8	9.0	5.3	5.0	3.6	3.9	3.3	2.5	5.3	3.5	4.9	6.8
Rain	0	0	316	192	96.2	55.6	37.9	40.2	48.5	93.5	302	0
Eva	19.7	20.6	20.9	20.0	18.8	21.7	26.1	28.9	26.9	25.1	22.2	19.7

4.2.3 Seasonal Variability of Rainfall, Temperature and Evapotranspiration over Gadaref Area.

Seasonal variations of rainfall, evapotranspiration and average maximum and minimum temperatures, are plotted, analyzed and compared to show the variability of climatic parameters during the seasons of MAM, JJAS and OND. The Figures 14 to 17 show the significant variations of each parameter during these seasons for the area of study over the long term. These are in agreement with the patterns of coefficient of variations for the same seasons and climate parameters in Gadaref area. The sorghum planting season corresponds with June to September season when the region receives peak precipitation. JJAS is also characterized with lower temperatures and lower evapotranspiration rates compared with other seasons.

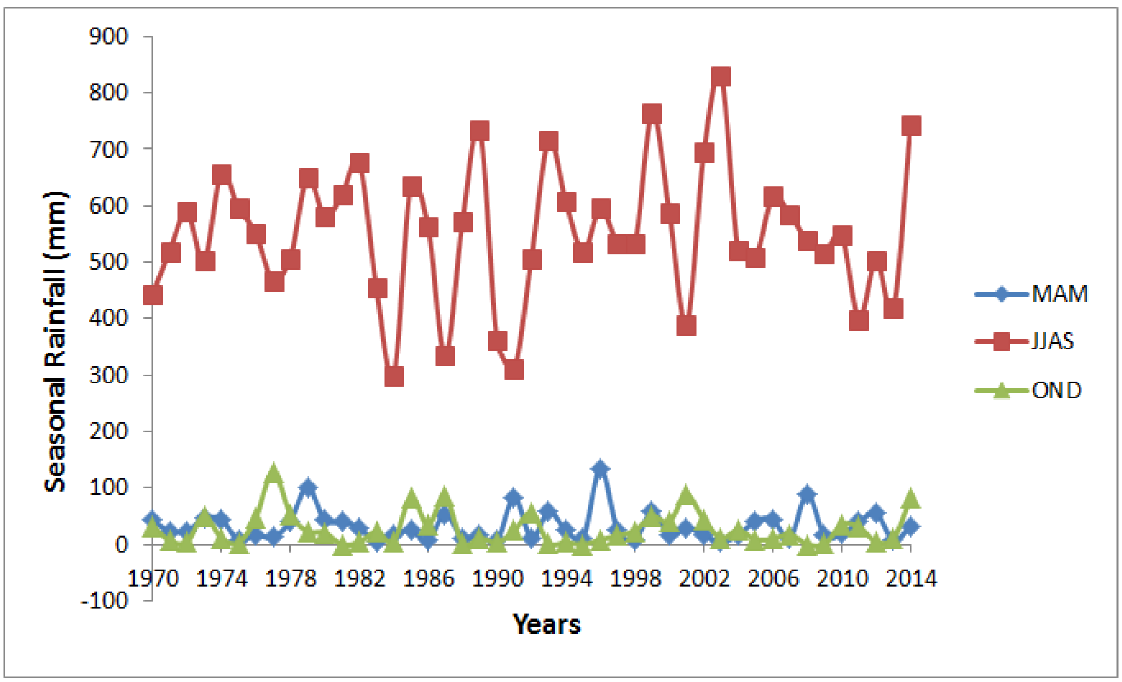

Figure 14: Seasonal Rainfall during the Seasons of MAM, JJAS and OND for Gadaref Area.

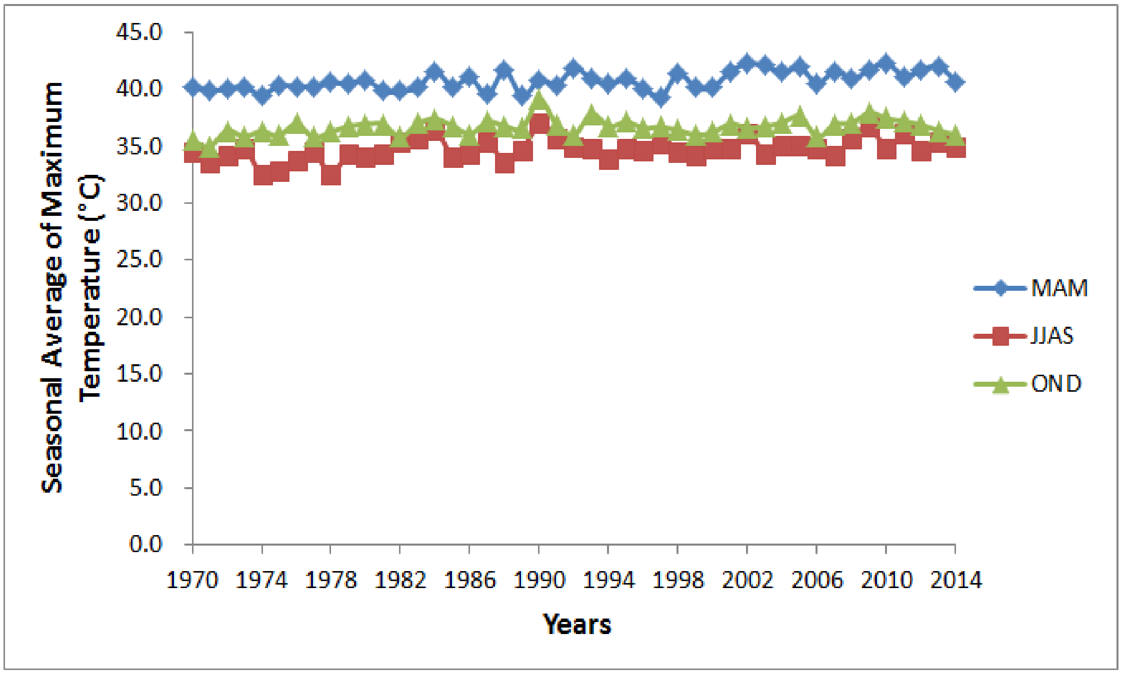

Figure 15: Seasonal Average of Maximum Temperature during the Seasons of MAM, JJAS and OND for Gadaref Area.

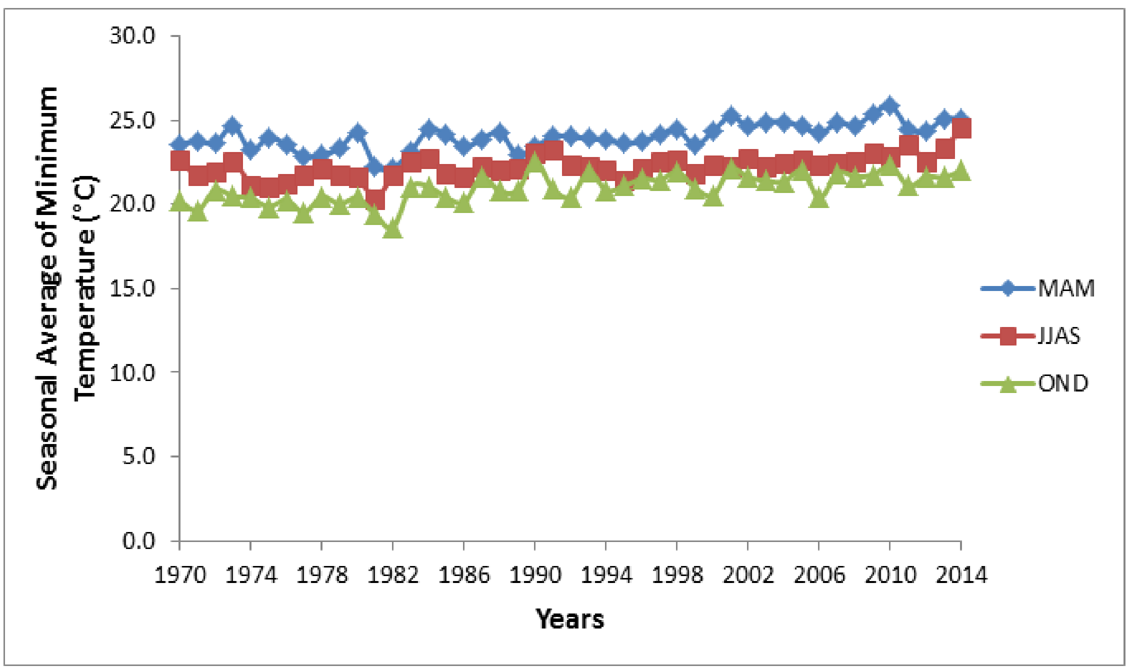

Figure 16: Seasonal Average of Minimum Temperature during the Seasons of MAM, JJAS and OND for Gadaref Area.

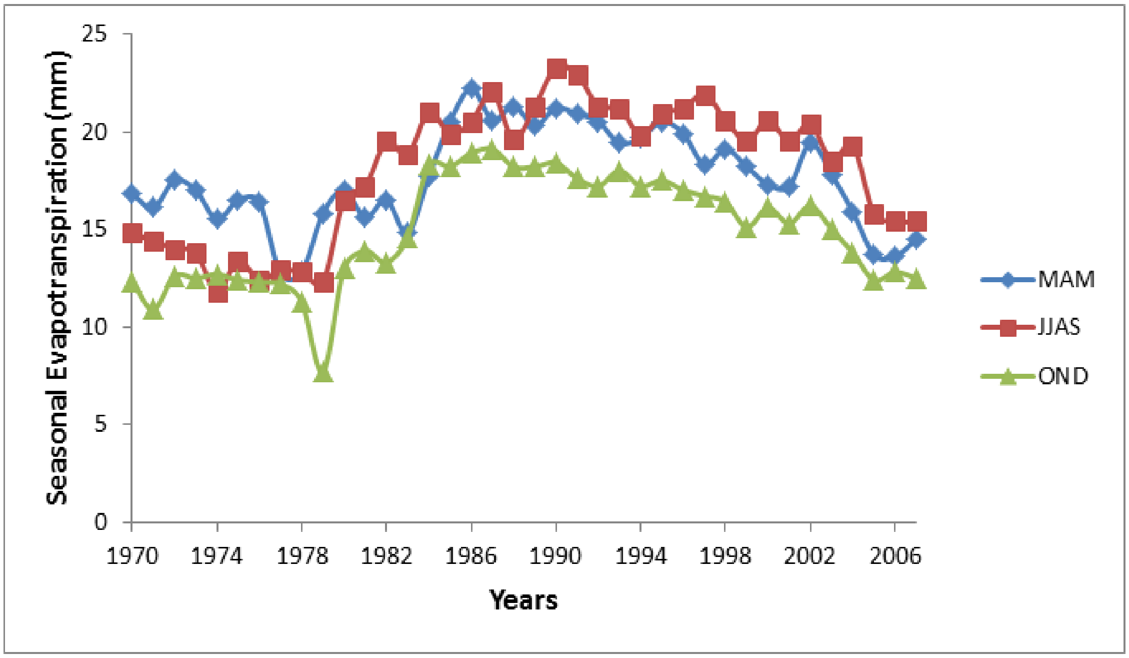

Figure 17: Seasonal Evapotranspiration during the Seasons of MAM, JJAS and OND for Gadaref Area.

4.3 Relationship between the Sorghum Yield and Climate Parameters over the Area of Study

4.3.1 Correlation Analysis

In order to determine the individual relationship between sorghum and the climate parameters used in this study, correlation analysis was carried out. **Table 2** shows the correlation coefficient between sorghum yield and climate parameters over the Gadaref area. Significance of the correlation was tested using student t and the values tabulated in table 2.

Table 2: Correlation Coefficient between Sorghum and Climate Parameters for Gadaref Area.

Parameters	Correlation coefficient	T Calculated	T tabulated	Relationship description
Sorghum yield and rainfall	0.59	4.792	1.645	Significant
Sorghum yield and maximum temperature	-0.34	-2.371	1.645	Significant
Sorghum yield and minimum temperature	-0.31	-2.138	1.645	Significant
Sorghum yield and evapotranspiration	0.25	1.693	1.645	Significant

Correlation analysis showed a positive relationship between sorghum and rainfall (0.59) and sorghum and evapotranspiration (0.25). This means that an increase in rainfall enhances sorghum production; while its decrease results in poor sorghum yield. On the other hand, both maximum and minimum temperature showed a negative relationship with correlation coefficients of -0.34 and -0.31 with sorghum respectively. This implies that an increase in temperature beyond the optimum level (high temperature of about 26-30°C and low temperature of about 10-15°C) results in a decline in sorghum production and vice versa.

Highest maximum temperature is often recorded during the rainfall season (June to September) while periods of lowest minimum temperature are observed during the October to December season, hence the high daily temperature range. Due to low absolute minimum temperature, crop damage increase through delayed maturity and cool temperature results in longer duration of crop maturity. As observed from the results obtained on the relationship between the climatic factors and sorghum yield, it is clear that rainfall with a correlation coefficient of 0.59 with sorghum is one of the most essential factors in sorghum production in Gadaref area.

In order to examine the significance of influence attributed to each of the climatic factors used in this study, a significance test was carried out. The results of the significance test for correlation coefficients are shown in Table 2.

A strong significant variation between the two values of t for temperature, rainfall and evapotranspiration was observed and showed the significant influence. This is evident through the calculated t value being greater than the tabulated value. It is, therefore, concluded that rainfall, maximum and minimum temperatures and evapotranspiration are crucial in sorghum production over the study area according to those results was carried out.

4.3.2 Multiple Regression Analysis

Multiple Regressions analysis was performed to determine how the climate parameters affect sorghum yield and Table 3 show the equation of multiple line regression and the coefficient of determination (R^2).figure 18 is explained the relationship between actual sorghum and predicted sorghum yield over Gadaref area.

Table 3: Multiple Regression Models for Sorghum and Climate Parameters for Gadaref Area.

Y is Sorghum predicted, $\mathbf{X_1}$ is Rainfall (mm), $\mathbf{X_2}$ is Minimum Temperature (°C), $\mathbf{X_3}$ is Maximum Temperature (°C) and $\mathbf{X_4}$ is Evapotranspiration (mm).

Climate Parameters	Multiple Regression models	Coefficient of determination $\mathbf{R^2}$ %	P≤0.05
Sorghum and rainfall, Tmax, Tmin and Evapotranspiration.	$\mathbf{Y}$=4292.40+.2010$\mathbf{X_1}$+163.69$\mathbf{X_2}$-33.106$\mathbf{X_3}$+225.91$\mathbf{X_4}$	0.30	0.02

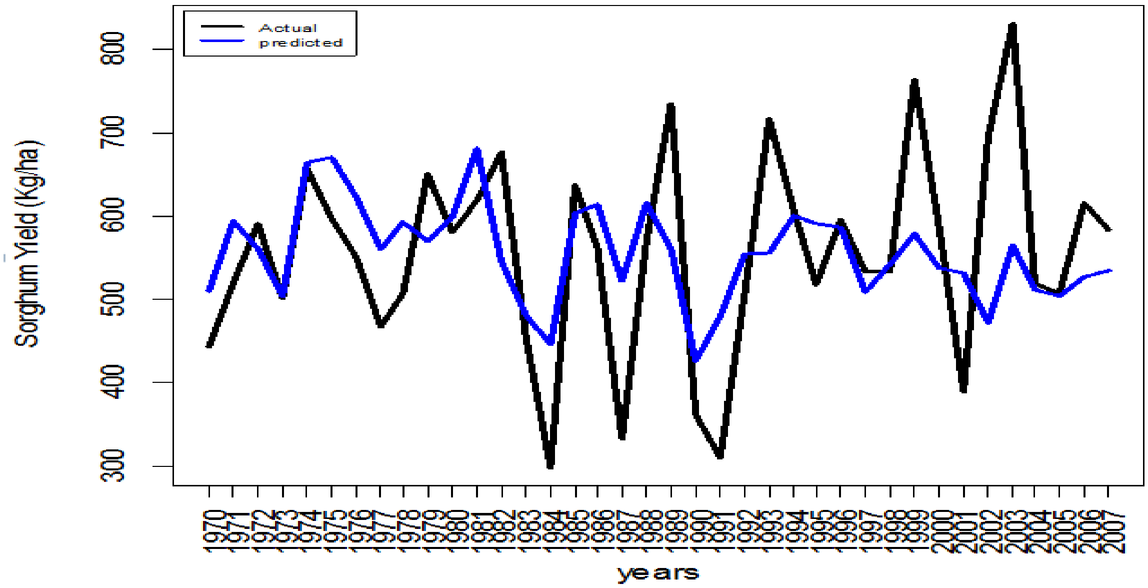

Figure 18: Shows the Predicted and Actual Sorghum due to Combination of Rainfall, Maximum Temperature, Minimum Temperature and Evapotranspiration for Gadaref Area from 1961 to 2014.

The coefficient of determination (R^2) was computed to identify the relationship between the sorghum yield and climate parameters. The result analysis of multiple regressions showed a high (30%) relationship between sorghum and set of climatic factors have been used in study. It was observed that 30% of the variability in sorghum yield could be explained by these climatic factors (rainfall, maximum temperature, minimum temperature and evapotranspiration) and significant relationship result to combination of all those climate factors and sorghum crop (p=0.02). Otherwise, there are many other climatic factors that may also play important roles in the process of sorghum production, such as rainfall distribution, humidity, wind speed, and soil temperature.

4.4 Assessing Impacts of Climate Variability and Change on Sorghum Yield

To assess the impact of climate variability and change on the sorghum yield, the AquaCrop model was used. Climate variability refers to the inter-annual variation of climate parameters over an area of interest. The AquaCrop Model utilizes rainfall, temperature, reference evapotranspiration and carbon dioxide concentration as the input data. The combinations of these variables were used to make climate files for the base year (1971-2000) and the years under climate variability. By inserting the name of the crop and the soil type, the model automatically generated the soil data.

4.4.1 Evaluation of CORDEX Model

Two methods were used to evaluate the accuracy of the CORDEX models in simulating the observed rainfall and temperature. The methods included mean root square error (RMSE) and correlation analysis with the results of each metric shown in Table 4 and 5. The NCC model was more accurate in simulating the observed variables relative to the other models. It also had high positive correlation of 0.44 for minimum temperature and 0.31for maximum temperature with the observed as compared to the other models. The NCC model also had low MRSE (0.16 for temperature) relative to the other models showing that it was more accurate than the other models. The study therefore utilized projection datasets from the NCC model to assess the impacts of future climate variability and change on sorghum yield in Sudan.

Table 4: Correlation between the Observed Climate Data and Cordex Generated Modeling Data.

Climate parameters	CCMA	CNRM	MIROC	MOC	MPI	NCC	NOAA
Rainfall	0.31	-0.12	-0.40	-0.11	0.15	**0.34**	0.26
Maximum Temperature	0.27	0.30	0.31	0.22	0.26	**0.31**	0.31
Minimum Temperature	0.18	0.16	-0.13	0.25	0.40	**0.44**	0.13
Evapotranspiration	0.23	0.24	0.13	0.17	0.18	**0.25**	0.19

Table 5: RMSE between the Observed Climate Data and Cordex Generated Modeling Data.

Climate parameters	CCMA	CNRM	MIROC	MOC	MPI	NCC	NOAA
Rainfall	21.84	15.78	14.18	14.48	15.13	**14.74**	17.44
Maximum Temperature	0.19	1.66	1.72	1.36	1.50	**0.16**	1.65
Minimum Temperature	2.40	0.47	0.52	0.49	1.48	**0.32**	1.85
Evapotranspiration	8.16	3.46	5.16	4.74	7.61	**2.57**	9.47

4.4.2 AquaCrop model validation

For calibration of the aquaCrop model, climate parameters data for the years 1971 to 2000 as base period were used. The table (6) explained the sorghum yield used to evaluation of aquaCrop model during the comparison with simulated sorghum yield.

Table 6: Sorghum Yield Data used for Evaluation of AquaCrop model

Years	Observed Sorghum Yield (kg/ha)	Simulated Sorghum Yield (kg/ha)	Years	Observed Sorghum Yield (kg/ha)	Simulated Sorghum Yield (kg/ha)
1971	697	234	1986	556	233
1972	815	201	1987	512	241
1973	594	189	1988	494	238
1974	517	208	1989	771	252

1975	485	155	1990	315	296
1976	913	224	1991	495	222
1977	903	214	1992	664	377
1978	350	192	1993	555	378
1979	852	250	1994	387	607
1980	446	187	1995	494	426
1981	183	189	1996	586	878
1982	775	180	1997	626	423
1983	78o	244	1998	522	799
1984	767	231	1999	540	546
1985	916	261	2000	720	416

Figure (19) shows the regression between the observed sorghum yield and the simulated sorghum yield. There was a positive linear relation between the observed sorghum yield and aquaCrop simulated sorghum yield for June to September season. R^2 value of 0.395 indicated 39.5% of the variability in the aquaCrop simulated sorghum yield is explained by the relationship between the AquaCrop simulated sorghum yield and observed sorghum yield values. Therefore, AquaCrop model is up to 39.5% fit for prediction of sorghum yield.

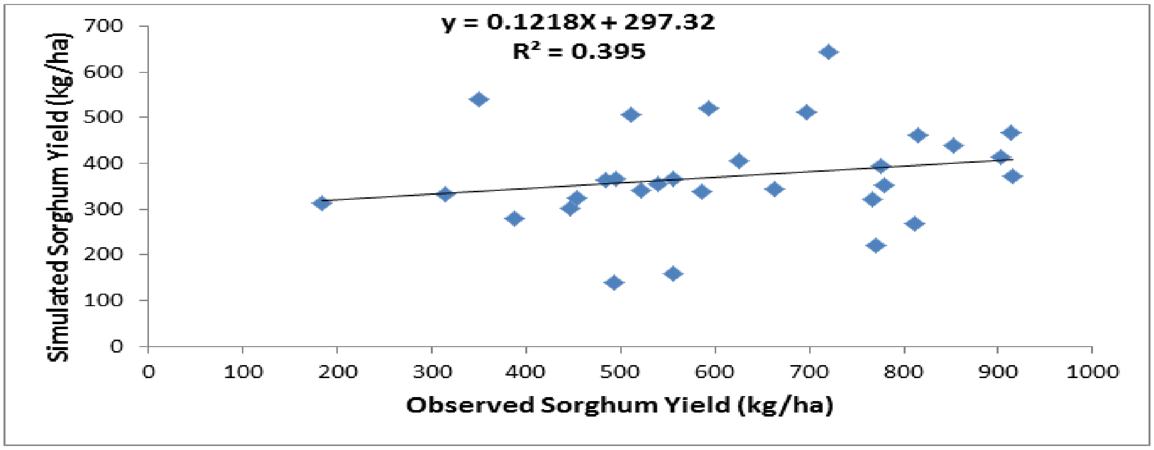

Figure 19: Relationship between Observed Sorghum Yield and Aqucarop Simulated Sorghum Yield for Gadaref Area.

For more clarification of relationship between the observed sorghum yield and AquaCrop simulated sorghum yield, the correlation has been done and the result showed is high positive linear relationship between observed values and simulated values, this correlation was statistically significant at 95% level of significance (P<0.02) (**Table 7**).

Table 7: Correlation between Observed Values and AquaCrop Simulated Sorghum Yields for Gadaref.

Variables	Correlation coefficient	P-value
Observed Sorghum Yield and Simulated Sorghum Yield	0.53	0.015

The Average Error (AE) computed for the sorghum yield was 401.7 kg/ha. The positive value of average absolute indicated that the model over predicted the sorghum yield. To adjust this value of over prediction, the value of the AE was to be subtracted from each simulated value of future sorghum yield, for the correct the simulated future values of sorghum, and this served to calibrate the AquaCrop model for use in Gadaref area. The AquaCrop simulated sorghum yield under climate change for the years 2017-2046, for season June-September over Gadaref. Average Error obtained during evaluation and calibration of AquaCrop model (401.7 kg/ha for sorghum yield) was subtracted and the true values of the expected sorghum grain yield were obtained (Table 8).

4.4.3 Variation of Climate Parameters due to Effect of Future Climate Change

For further demonstrations and evidences of patterns and behaviors variation of climate parameters due to effect of future climate change, the table 8 is shows the comparison between the average of observed climate parameters (rainfall, minimum temperature and maximum temperature) for period from 1971 to 2000 and future climate parameters for period from 2017 to 2046. The results of average comparison were explained, the rainfall will reduced during the next thirty years over study area by 33% (202.46 mm). While, it indicated to no significant change will occurs in maximum temperature over study area during this period. 11.2% (2.39 °C) the increase will be happened in minimum temperature under future climate change. Figures 20, 21, 22, 23, 24 and 25 are shows the annual variation of observed climate data and future climate data over study area for the same periods mentioned above.

Table 8: Comparison between the Averages of Annual Observed Data and Annual Future Data for Gadaref Area.

parameters	Average of Observed Data	Average of Future Data	The Change	The percentage Change.
Rainfall (mm)	612.43	409.97	202.46	33%
Maximum Temperature (°C)	36.71	36.73	0.02	0.05%
Minimum Temperature (°C)	21.36	23.75	2.39	11.2%

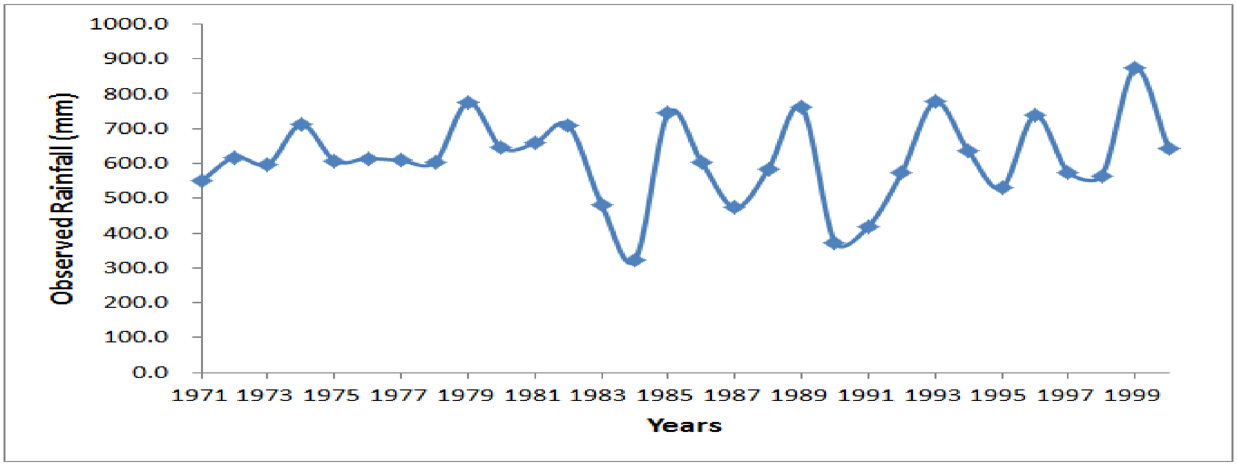

Figure 20: Annual Variation of Observed Rainfall over Gadaref Area for Period from 1971 to 2000.

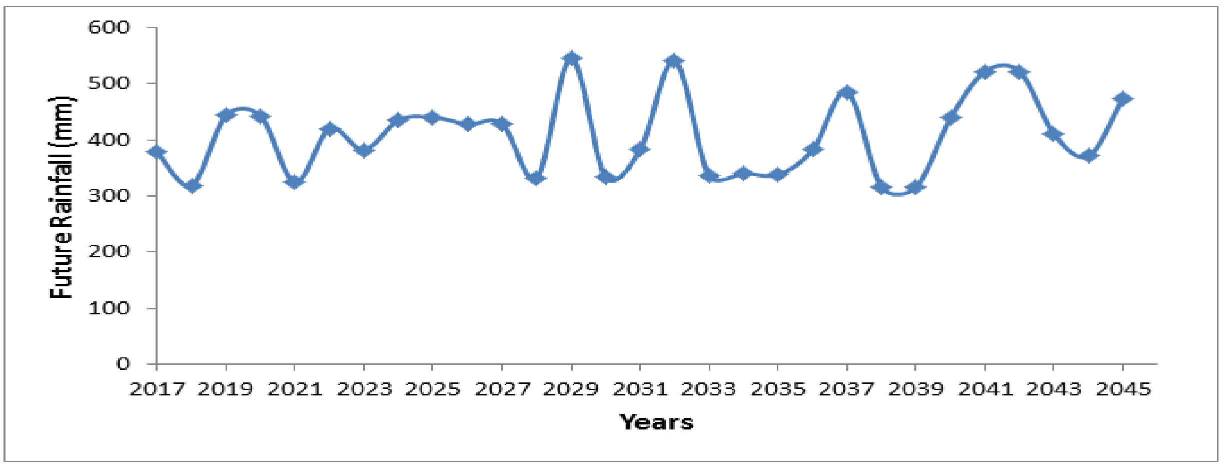

Figure 21: Annual Variation of Future Rainfall over Gadaref Area for period from 2017 to 2046.

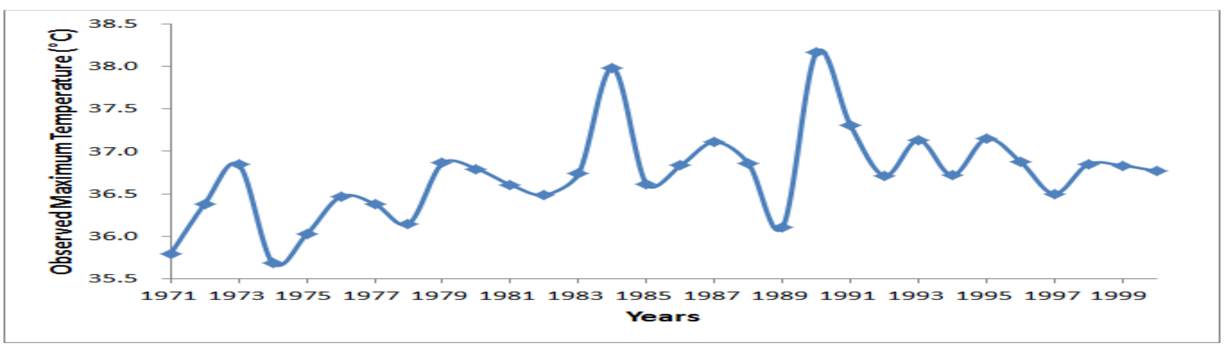

Figure 22: Annual Variation of Observed Maximum Temperature over Gadaref Area for Period from 1971 to 2000.

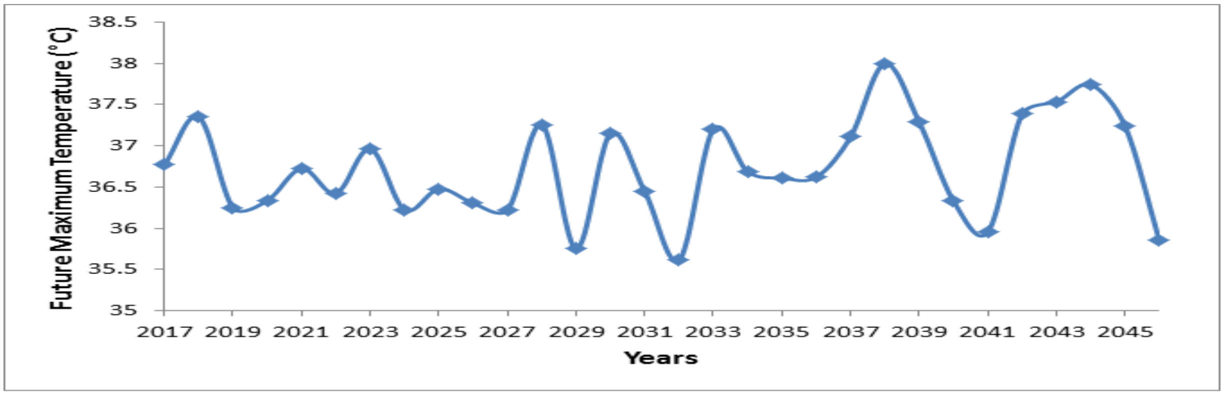

Figure 23: Annual Variation of Future Maximum Temperature over Gadaref Area for Period from 2017 to 2046.

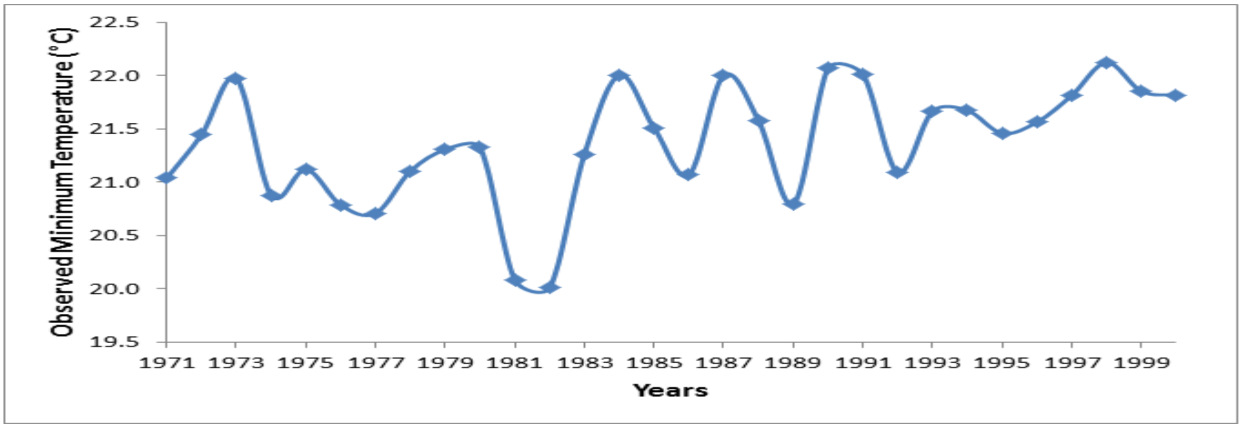

Figure 24: Annual Variation of Observed Minimum Temperature over Gadaref Area for Period from 1971 to 2000.

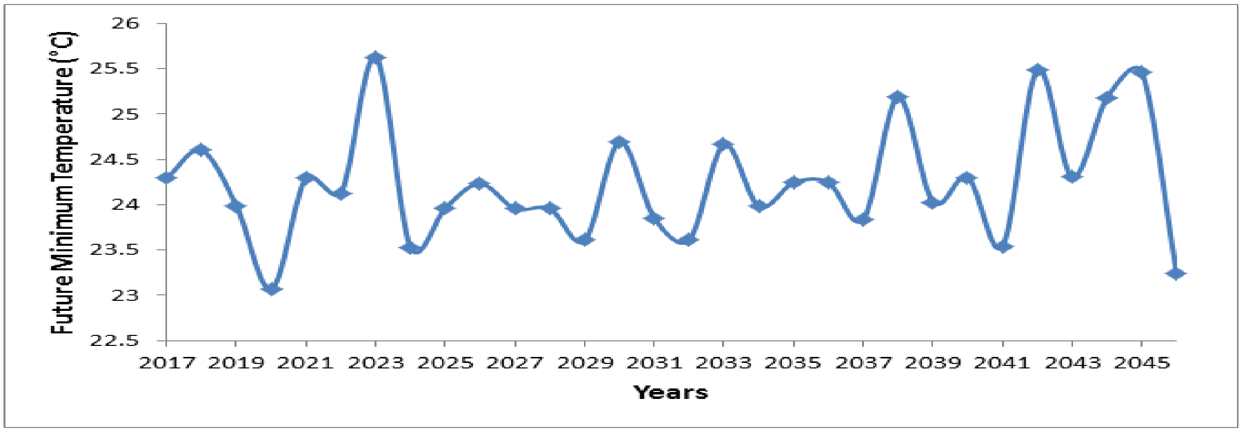

Figure 25: Annual Variation of Future Minimum Temperature over Gadaref Area for Period from 2017 to 2046.

The impact of change on the seasonal climate parameters showed the seasonal rainfall will decrease by the 233.6 mm (42%) by 2046, while it indicated the seasonal maximum temperature and minimum temperature will increase by 2.48°C (6.3%) and 2.24°C (10.2%) respectively, table 9. This greater decline in seasonal rainfall and rise in seasonal temperature over study area agreed with the greater reduction of sorghum crop production will occurs in future and hence, the rainfall and temperature are considering the crucial climate parameter in process of sorghum cultivation during next decade over Gadaref area.

Table 9: Comparison between the Averages of Seasonal Observed Climate Data (1971-2000) and Average 0f Seasonal Future Climate Data (2017-2046) for Gadaref Area.

Parameters	**Average of Observed Climate Data**	**Average of Future Climate data**	**Change between Observed and Future**	**Percentage Change**
Rainfall (mm)	551.73	318.13	-233.6	42%
Maximum Temperature (°C)	34.5	36.98	+2.48	6.3%
Minimum Temperature (°C)	22.0	24.24	+2.24	10.2%

4.4.4 Predicted Future Sorghum Yield under climate change

The predicted future sorghum yield simulated due to climate change by the AquaCrop model after subtracting the value of Average Error (401.7 kg/ha for sorghum yield) was obtained during the evaluation and validation of model, as shown in Table 10.

Table 10: Simulated Sorghum Yield from AquaCrop Model under Future climate Data for Gadaref Area from 2017 to 2046.

Years	Simulated Sorghum Yield (kg/ha)	Years	Simulated Sorghum Yield (kg/ha)
2017	511.3	2032	365.3
2018	462.3	2033	296.3
2019	521.3	2034	140.3
2020	506.3	2035	221.3
2021	362.3	2036	332.3
2022	467.3	2037	365.3
2023	414.3	2038	344.3
2024	539.3	2039	158.3
2025	440.3	2040	278.3
2026	303.3	2041	323.3
2027	314.3	2042	338.3
2028	393.3	2043	405.3
2029	353.3	2044	340.3
2030	332.3	2045	353.3
2031	373.3	2046	644.3

The average predicted future simulated sorghum yield for season June-September (2017-2046) is 372.3 kg/ha. Comparison with the observed sorghum yields for season June-September (1970/2000) of 616.2kg/ha indicates there will be a decrease in future sorghum yield, in the area of study.

The percentage average between mean predicted future simulated sorghum yield for the years 2017 to 2046 to the mean observed sorghum yield for years 1970 to 2000 over the area study will have decreased by 39.6%.

Further, the regression of simulated sorghum yield against the f season rainfall for sorghum crop of season June-September for all simulated years indicated to positive relationship between the future seasonal rainfall and future simulated sorghum yield (figure 26). Therefore, decrease in seasonal rainfall, is expected to decrease sorghum yield. The R^2 value was much smaller for season June-September, since the past generally had more rainfall compared to the future.

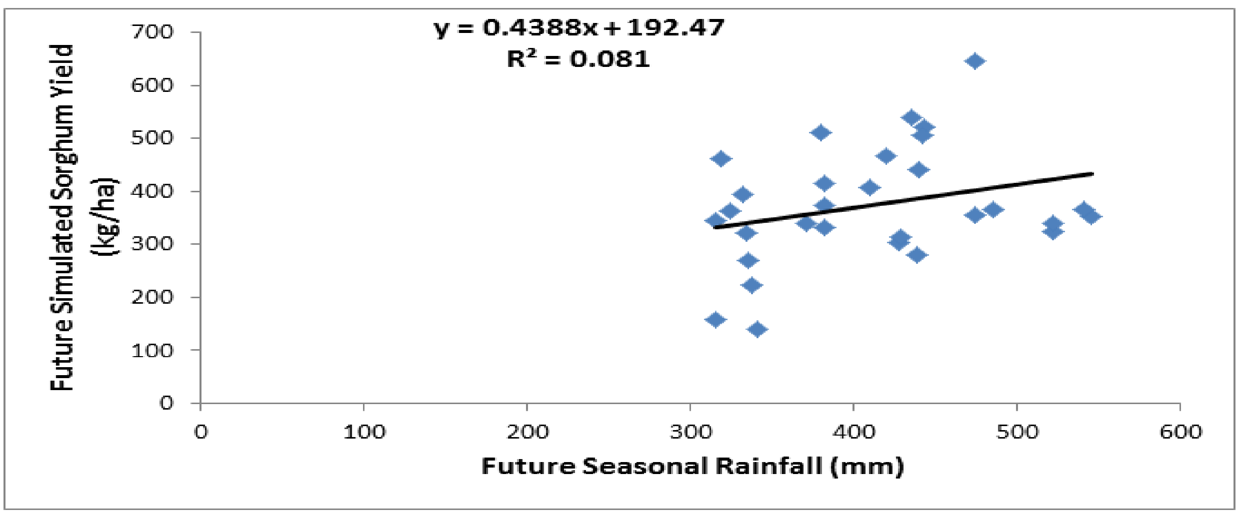

Figure 26: Relationship between Future Simulated Sorghum Yield and Future Seasonal Rainfall for Gadaref Area.

4.4.5 Variation of future simulated sorghum yield over Gadaref area

Figure 27 was showed the annual variation for the seasonal of future simulated sorghum yield over the Gadaref area during the simulation period (2017-2046). Which that indicated to the high variation of future sorghum yield through the simulation period, with greater decrease in amount of sorghum crop production after the year 2026 to 2045, hence that, reveal clear picture for decrease of sorghum crop production under effect of climate change, will happen in future.

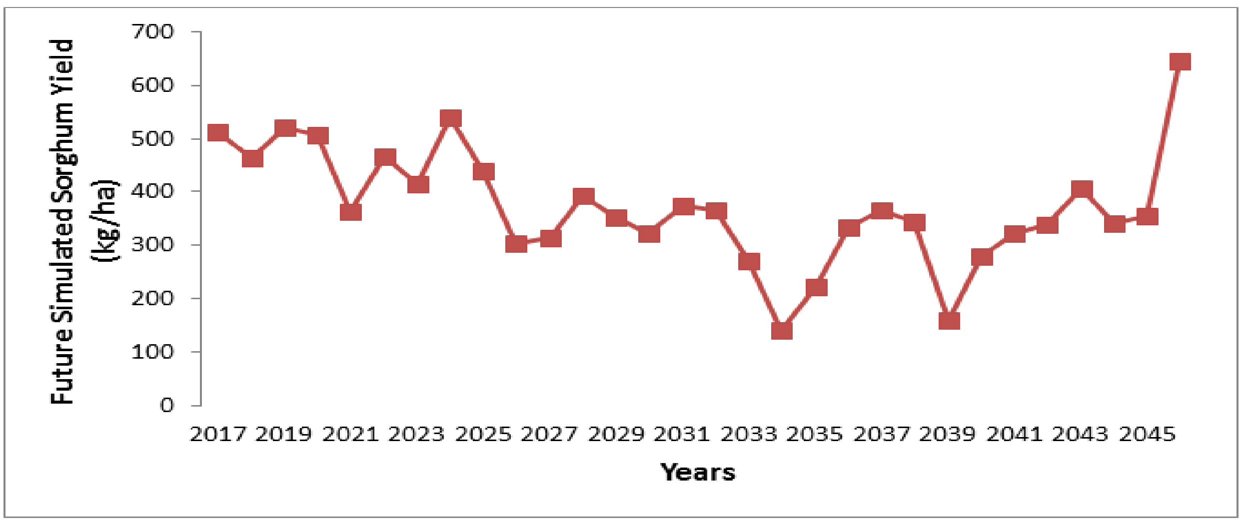

Figure 27: Annual Variation of Future Simulated Sorghum Yield for all Simulation Years over Gadaref Area from 2017 to 2046.

4.4.6 Multiple Regression Analysis

Figure 28 below shows the multiple regression analysis output of the simulated sorghum yield and predicted sorghum yield for period 2017 to 2046 using future climate parameters (rainfall, maximum and minimum temperature and evapotranspiration) over the Gadaref area. The analysis revealed similarity in the patterns and behaviors of sorghum yield for the simulated yield and predicted yield over the Gadaref area. The variability in the future sorghum yield predicted from the climate parameters (rainfall, maximum and minimum temperature and evapotranspiration) explains nearly 33.5% variability in the simulated sorghum yield as indicated by the R^2 value of 0.335(Table 11) over study area. This is in agreement with the results between the observed sorghum yield and predicted sorghum yield for the same climate parameters using observed data for period 1971 to 2000.

Table 11: Multiple Regression Models for Sorghum and Future Climate Parameters for Gadaref Area.

Y is Sorghum Predicted, X_1 is Rainfall (mm), X_2 is Maximum Temperature (°C), X_3 is Minimum Temperature (°C) and X_4 is Evapotranspiration (mm).

Climate Parameters	Multiple Regression models	Coefficient of determination R^2 %	P≤0.05
Sorghum and rainfall, Tmax, Tmin and Evapotranspiration.	$Y=877.618+0.4612X_1+31.543X_2-29.975X_3-17.0582X_4$	0.335	0.03

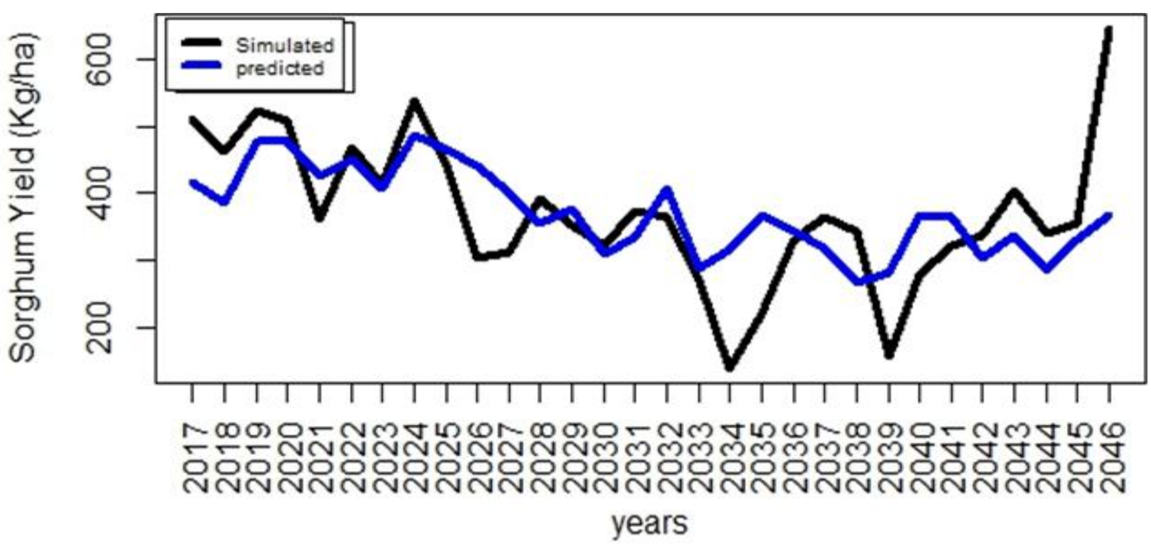

Figure 28: Shows the Simulated (by AquaCrop Model) and predicted (by Multiple Regression Model) Sorghum due to Combination of Rainfall, Maximum Temperature, Minimum Temperature and Evapotranspiration for Gadaref Area from 2017 to 2046.

CHAPER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

The homogeneity test for climate data in area of study was used, it revealed high homogenous for the period from 1970 to 2005 over study area. While the trend analysis results of climate parameters indicated to significant trend (increase) for maximum temperature, minimum temperature and evapotranspiration. However rainfall and sorghum, it was indicated to insignificant trend (decrease) over study area. Also analysis results of coefficient variance were explained, there are temporal variability for climate parameters within the study area.

The output of aquacrop model for future of sorghum crop production in study area, it was demonstrated the climate change will have greater negative impact in sorghum crop production over study area by the year 2046.

5.2 Recommendations

if the expected, sorghum yield decrease according to the study results for future, the farmers, government, experts and specialists in the agricultural sector, they should adopt the strategies and decisions which will enable them to avoid the impacts of shortage in sorghum crop production will may happen in future. This may involve the identification of alternative livelihood sources and adoption of climate resilient crop varieties.

the uncertain in the future variability of rainfall and temperature calls for further studies and researches in the study area so as to explain and interpret the negative impacts of climate change that may happen. Therefore, the Future studies and research in the same area should attempt to involve other climate parameters, such as wind speed, soil temperature, relative humidity and rainfall distribution, to give further verifications and confidence.

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Annex 1: Crop Characteristics

Crop Characteristics	**Input**
Initial Canopy Cover (%)	0.97
Canopy Size Seeding (cm^2/plant)	6.5
Plant Density (plants/ha)	150000
Max Canopy Cover (%)	80
Max Root Deeping (m)	1.20
Base Temperature (°C)	17.5
Upper Temperature (°C)	35.0
Harvest Index (%)	50.0
Soil Water Stress	
• Canopy Expansion	Moderately Tolerant to Water Stress.
• Stomatal Closure	Moderately Sensitive to Water Stress.
• Early Canopy Senescence	Tolerant to Water Stress
• Aeration Stress	Moderately Tolerant to Water Logging.
• Salinity	Moderate Sensitive to Salinity Stress.
• Effect of soil Fertility Stress	Moderate Stress.
Growing Cycle	(days)
• Emergence	5
• Max Canopy	50
• Flowering	70
• Senescence	110
• Maturity	125
• Max Depth	80

Annex 2: Soil Characteristics

Clay Soil	**Input Values**
Saturation (volume %)	55.0
Field Capacity (volume %)	54.0
Production Water productivity (volume %)	39.0
Total Available Water (mm/m)	150
K Saturation (mm/day)	2.0
Soil evaporation (readily evaporable water (mm))	14
Root depth (m)	1.2
Depth Ground Water below Soil Surface (mm)	4

Annex 3: Field Management

Field Characteristics	**Input**
Soil Fertility of Biomass Production (Moderate %)	60
Soil Surface Practices • Surface Runoff Occurrence • Soil Bunds	 No No