UNIVERSITY OF NAIROBI

IMPACT OF CLIMATE VARIABILITY AND CHANGE ON SORGHUM YIELD IN LESOTHO

BY

MAHALI ESTHER MAKOLOI

I56/12690/2018

A DISSERTATION SUBMITTED FOR EXAMINATION IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR AWARD OF THE DEGREE OF MASTER OF SCIENCE IN AGROMETEOROLOGY IN THE DEPARTMENT OF METEOROLOGY
UNIVERSITY OF NAIROBI
KENYA

JULY 2021

DECLARATION

I declare that this dissertation is my original work and has not been submitted elsewhere for examination, award of a degree or publication. Where other people's work or my own work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi requirements.

Signature: Makoloi **Date:** 07/07/2021

Mahali Esther Makoloi

I56/12690/2018

Department of Meteorology

School of Physical Sciences

University of Nairobi

This dissertation is submitted for examination with our approval as research supervisors:

	Signature	**Date**
Dr. Emily Nyaboke Bosire	…ENB…………………	07/07/2021
Mr. Cromwel Busolo Lukorito		07/07/2021

Dr. Emily Nyaboke Bosire

Department of Meteorology

University of Nairobi

P.O Box 30197-00100

Nairobi Kenya

ebosire@uonbi.ac.ke

Mr. Cromwel Busolo Lukorito

Department of Meteorology

University of Nairobi

P.O Box 30197-00100

Nairobi Kenya

cbusolo@uonbi.ac.ke

DEDICATION

This dissertation is dedicated to my parents, Ntate Makoloi Lawrence Makoloi and ‘M’e ‘Makhethang Elizabeth Makoloi, who always stressed the importance of higher education; my spiritual father Fr. Victor Makhabane Mopeli, my sisters, my brothers, and my friends for their love, motivation and prayers that kept me strong. Thank you for believing in me.

ACKNOWLDGEMENTS

I would first like to thank the Almighty God for making this work possible, protecting and giving me strength throughout the entire period of study at the University of Nairobi.

I would also like to convey my heartfelt gratitude and gratefulness to my supervisors Dr. Emily Nyaboke Bosire and Mr. Cromwel Busolo Lukorito for giving me support, guidance, encouragement and constructive criticisms and suggestions that made this dissertation a success. Many thanks are due to the University of Nairobi for allowing me to enroll for this postgraduate study, especially, the Department of Meteorology Lecturers and staff who introduced me to the world of Agrometeorology. Their valuable support is highly appreciated. To my classmates and all people who contributed to this research, I would like to say thank you for your unconditional support and encouragement that made this study achievable.

My special thanks are also due to the Ministry of Agriculture and Food Security, through Smallholder Agriculture Development Project (SADP), Lesotho, for awarding me a scholarship to pursue my Master of Science in Agrometeorology. Furthermore, I would like to convey my sincere thanks and gratitude to the Director, Department of Agricultural Research and all the staff for trusting me for enrolling in this program. Without your support this work would not have been possible.

I wish also to thank all the staff of Lesotho Meteorological Services and Bureau of statistics, Lesotho, for providing me with the requisite meteorological and agricultural data respectively.

My special appreciation also goes to my entire family and friends for their support and inspirations despite the long distance that separated us. The Almighty God heard our prayers.

ABSTRACT

Climate variability characterized with hazardous extreme weather events is a major threat to rain-fed agriculture production in Lesotho resulting into increased food insecurity and poverty in the country. Therefore, this research sought to evaluate the impact of climate variability and change on sorghum yields in Lesotho. The data used in this study comprise observed rainfall and maximum temperature as well as minimum temperature datasets for Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek from 1986-2018 obtained from the Lesotho Meteorological Service, and sorghum yield data from 1999/00 to 2017/18 obtained from the Lesotho Bureau of Statistics. Other data sets included historical and projected rainfall and temperature datasets from 1986-2005 and 2030-2060 respectively obtained from the Climate System Analysis Group (CSAG).

The variability and trends on sorghum yield, seasonal rainfall and temperature datasets were analyzed using the coefficient of variation and Mann-Kendall statistical test respectively. Rainfall distribution was analyzed using the Precipitation Concentration Index. The relationship between sorghum yield and climate parameters was established by, first, determining the degree of association between climatic elements and sorghum yields using correlation analysis, and linking the pairs of variables that gave rise to statistical significant correlations using regression analysis. The significance of correlation was determined using student t-test. The impact of climate change on sorghum yield was analyzed using the AquaCrop model and data from suitable CMIP5 GCMs under RCP 4.5 climate scenario. CMIP 5 GCMs performance was assessed using correlation and Root Mean Square error methods.

The results showed moderate rainfall variability, with uniform to moderate precipitation concentration index (PCI<16) in all the study areas. Both seasonal maximum and minimum temperature revealed less variability. Non-significant increasing trends (α=0.05) were depicted for rainfall in all the areas under study. Statistically significant increasing trends were depicted for minimum temperature in all the four stations whereas maximum temperature showed significant increasing trends in Thaba-Tseka and Mohale's Hoek. However, the trends were not significant at Leribe and Butha-Buthe. Sorghum yields exhibited high variability (CV>30%) in all the study areas, with non-significant decreasing sorghum yield trends (α=0.05) at Thaba-

Tseka, Leribe and Butha-Buthe and an insignificant increasing trend for sorghum yields in Mohale's Hoek.

Statistically significant positive correlation coefficients was depicted between rainfall and sorghum yields in Leribe, Mohale's Hoek, Butha-Buthe and Thaba-Tseka. Both maximum and minimum temperature showed positive but insignificant correlation coefficients with sorghum yields, except in Butha-Buthe and Leribe where maximum temperature indicated a significant positive correlation with sorghum yields. The study depicts a statistically significant relationship with rainfall, maximum temperature and sorghum yield ($p<0.05$) in Butha-Buthe but in Leribe, Thaba-Tseka and Mohale's Hoek only rainfall and sorghum yields showed significant relationships.

The ensemble, CNRM-CM5, FGOALS-s2 and GFDL-ESM2M GCM's performed relatively well in simulating temperature and rainfall in the study area, and were therefore used for projecting future climate (2030/31-2059/60) during the cropping seasons. All the models indicated uncertainty in projecting future rainfall. The ensemble revealed increasing rainfall in Butha-Buthe, Leribe and Mohale's Hoek and a decline in rainfall in Thaba-Tseka. A rising temperature was projected in all the study regions during the 2030/30 to 2059/60. The output from Aquacrop model driven by the GCMs ensemble projected increasing sorghum yields in Leribe and Butha-Buthe and a decline in sorghum yield in Thaba-Tseka and Mohale's Hoek during 2030/31 to 2059/60 cropping season.

Climate change therefore presents both positive and negative impacts on sorghum production in Lesotho. This calls for integration of climate change response measures into agricultural policies and strategies to support farmers to adapt to the changing climate impacts in order to increase and sustain sorghum productivity and nutrition security under changing climate.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS AND ACRONYMS

APSIM	Agricultural Production System sIMulator
BoS	Bureau of Statistics
Can-ESM2	Canadian Earth System Model Second Generation
CBL	Central Bank of Lesotho
CCCM	Canadian Centre for Climate Modeling and Analysis
CIMP5	Coupled Model Inter-comparison Project Phase 5
CMIP3	Coupled Model Inter-comparison Project Phase 3
CNRM-CM5	Center National de Recherches Meteorologique Coupled Model version five
CORDEX	Coordinated Regional Downscaling Experiment
CROPSys	Cropping Systems Model
CV	Coefficient of Variability
DSSAT	Decision Support System of AgroTechnology Transfer
ENSO	El Niño-Southern Oscillation
ETo	Evapo-Transpiration
FAO	Food and Agriculture Organization
FGOALS-s2	Flexible Global Ocean-Atmosphere Land System Model, Second Spectral version
GCM's	Global Circulation Models
GDP	Gross Domestic Product
GFDL	Geophysical Fluid Dynamics Laboratory
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory Earth System Model
GISS	Goddard Institute for Space Studies model
GoL	Government of Lesotho
IPCC	The Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
LMS	Lesotho Meteorological Services
LVAC	Lesotho Vulnerability Assessment Committee
MAFS	Ministry of Agriculture and Food Security
MAM	March-April-May

MAMJ	March-April-May-June
MIROC-ESM	Model for Interdisciplinary Research on Climate Earth System Model
MJJAS	May-June-July-August-September
MOPREDAS	Monthly Precipitation Data base of Spain
NASA	National Aeronautics and Space Administration
Nor ESM1-M	Norwegian Earth System Model 1- Medium Resolution
OND	October- November-December
ONDJFMA	October- November-December- January- February-March-April
OSU	Oregon State University model
PCI	Precipitation Concentration Index
RCP	Representative Concentration Pathways
RMSE	Root Mean Square Error
SOND	September- October- November-December
UKHADCM3	United Kingdom Hadley Centre for Climate Prediction
UKHI	United Kingdom Meteorological Office High Resolution model
UKTR	United Kingdom Meteorological Office Hardley Centre Transient model
UNFCCC	United Nations Framework Convention on Climate Change
WFP	World Food Programme
WMO	World Meteorological Organization
WOFOST	World Food Studies crop growth model

CHAPTER 1: INTRODUCTION

1.1 Background

Agriculture in Southern Africa countries is vulnerable to climate variability impacts and severe weather events which are the most important causes of food insecurity (Dejene *et al*., 2011; Kandji *et al*., 2006). According to Prasad *et al*. (2008) the changing climate in Southern Africa will disrupt current temperature and rainfall patterns. Most of the Southern Africa population who depend on rainfed agriculture are going to feel the impact of climate variability (Matarira *et al*., 2013). Lesotho being one of the Southern African countries is by now encountering the progressing impacts of global climate change for example, occurrence of natural disasters and extreme climate events including drought as well as the emerging signs of progressive desertification (Lesotho Meteorological Services, 2000). Lesotho is expected to experience more intense weather and climate conditions as a consequence of climate change. Erratic climatic circumstances limit exploitation of productive land area and the length of growing period and therefore place limits on potential crop and land production (Mphale *et al*., 2003). Developing countries including Lesotho are faced with greater challenges of climate change impact than developed countries. However, responding to these challenges still remains to be a major problem (Lesotho Meteorological Services., 2017).

Occurrence of storms, floods, drought, as well as variability in hydrological conditions and precipitation have had immense effect on food security in Lesotho (Lesotho Meteorological Services, 2017). Precipitation has become more and more erratic and unpredictable, causing recurring droughts and precarious agricultural conditions. Rainfall occurs mainly in October to March and is extremely variable in amount, timing and spatial distribution (Mekbib *et al*., 2011). Some parts of the Lesotho experience mean annual temperatures of less than ten degrees Celsius due to their high elevations that ranges from 1400 m to 3480 m above mean sea level (Dejene *et al*., 2011). Climate change projections for Lesotho indicate increased temperature, marked rainfall variability, increased frequency and intensity of extreme climate events (Lesotho Meteorological Services, 2017).

Agriculture relies highly on climate and weather for production of food to support living (Yohannes., 2015). Over 85% of Basotho people relies on farming as source of revenue (Lesotho Meteorological Services., 2007; Mphale., 2003). The majority of this people live in the rural parts and is susceptible to the changing weather influences. The agriculture sector is a major employer and contributor to Gross Domestic Product (GDP) in Lesotho. However, GDP contribution has dropped from 25 % during the 1980s to 10 % in the 1990s and more to single digit levels in recent years (Matela, 2012). The country's production requirement for cereals is 360,000 metric tonnes against the country's production of only 110,000 metric tonnes per year (Mock, 2005). Lesotho generates about 30 % of the total food needed for consumption in a normal year. This implies that 70 percent of the food needs including cereals has to be imported from the region at the prevailing regional market prices.

Periodic droughts, land degradation and diminishing soil fertility has resulted in reduction of acreage of good quality arable land (FAO/WFP, 2005; Lesotho Meteorological Services, 2007) with the consequence of deteriorating sources of living in the rural areas. The major menace to farming productivity in Lesotho include unfavorable weather in the form of irregular rains and abnormal temperature (FAO, 2012). Mphale (2003) identifies drought, early frost and uneven rainfall distribution as primary causes of food insecurity in Lesotho. Late onset and early cessation of rains especially in the mountains where normal planting season starts in August/September and dominant dry spells during the growing season also adversely affect agricultural production in Lesotho. In mountain areas, the growing seasons are short and crops are normally affected by early frost before reaching physiological maturity. Snow that occurs in winter in these areas contribute to soil moisture availability for summer crops. This makes it easy for farmers to start planting crops in August/September. Planting at this time extends the growing season, thus enabling long duration crops like maize and sorghum to reach their respective physiological maturity.

Sorghum (*Sorghum bicolor* (L) Moench) is an annual summer crop. It is a vital cereal crop most common in Sub-Saharan Africa and India (Laidlaw and Godwin, 2008). Sorghum in Lesotho has been grown countrywide for many years and is considered a main cereal crop (FAO, 2012; WFP, 2006). It is produced on about 60 to 80 thousand hectares each year.

Sorghum is known as a drought tolerant crop because it can survive under conditions of inadequate moisture and high temperature (Laidlaw and Godwin, 2008). According to Sekoli and Morojele (2016), farmers should integrate sorghum into cropping systems under marked climatic variability that manifests in severe and frequent droughts and intra-seasonal dry spells, and extremely irregular weather conditions. During drought conditions, most of the farmers in Lesotho switch to planting more sorghum than maize, though in most areas of the country sorghum production is at risk of being damaged by flocks of birds (Dejene *et al.*, 2011). Average productivity levels of sorghum in Lesotho is 3000kg/ha (Mphale *et al*., 2003).

1.2 Statement of the Problem

Lesotho's agricultural production has deteriorated considerably over the past years with agriculture sector's contribution to GDP declining to 10.0 % in the 1990's from 25.0 % in the 1980's (Matela, 2012). The country's agriculture is threatened by several environmental challenges including soil erosion and general land degradation caused by overgrazing, as well as floods and droughts arising from climate variability (Nhemachena *et al*., 2017). Crop production in the country is also constrained by infertile soils, insufficient use of organic manures, ineffective use of farming equipment and tools that are associated with untimely sowing, poor soil preparations, insufficient hoeing, and late reaping among others. Climate variability induced fluctuation in crop yields have over the years adversely impacted national economic growth and food security through decreased availability of food in Lesotho. Unfavorable climatic conditions have often contributed significantly to crop failure in Lesotho. The marked variability of rainfall in Lesotho causes drought and floods with adverse impacts on crop yields. Cropping seasons have over the years become shorter; frost incidences have worsened; crop yields have declined greatly. Further climate variability and change impacts will exacerbate the current vulnerability of agriculture in Lesotho.

1.3 Research Questions

This study was guided by the following research questions:

i. How do temperature and rainfall vary in Lesotho?
ii. What is the observed trends in sorghum yields in Lesotho?
iii. How does climatic variability affect sorghum yields in Lesotho?

iv. How would the future change in climate likely to affect sorghum yields in Lesotho?

1.4 Objectives

The main objective of this study was to assess the impact of climate variability and change on sorghum yields in Lesotho. To achieve this overall objective, the following specific objectives were carried out:

a) To determine the variability and trends in climate parameters including rainfall, maximum and minimum air temperatures.
b) To determine the variability and trends in the observed sorghum yields in Lesotho.
c) To establish the relationship between climatic variability parameters and sorghum yields in Lesotho.
d) To assess the impact of current and future climate on sorghum productivity in Lesotho.

1.5 Justification of the Study

Agriculture practiced in Lesotho is categorized as a mixed farming system that is susceptible to adverse climate variability and change influences. Agriculture sector contributes to the country's Gross Domestic Product (GDP) and a source of income as well as food security to many households. The sector is also a major employer of the Lesotho population. However, GDP contribution has dropped from 25 % during the 1980s to 10 % in the 1990s and more to single digit levels in recent years (Matela, 2012). The country's production requirement for cereals is 360,000 metric tonnes against the country's production of only 110,000 metric tonnes per year (Mock, 2005). Lesotho generates about 30 % of the total food needed for consumption in a normal year. This implies that 70 percent of the food needs including cereals has to be imported from the region at the prevailing regional market prices. The decreasing food productivity and associated GDP decline have been linked to the erratic climatic regimes that have characterized the country in recent years.

This study, therefore, attempted to comprehend the impacts of climate variability and change on sorghum production, one of the main cereal crops planted in Lesotho. The understanding of climate crop relationships under the changing climate, that constitutes the main challenge encumbering progress of agriculture sector in Lesotho will provide and also contribute to knowledge on the impact of current climate variability and in the long term, climate change on sorghum production. Also, the results of this study will inform the agricultural policy process and other stakeholders in putting in place measures that would enable climate responsive adaptation plans and decisions that support sustainable sorghum productivity in the country under changing climate.

1.6 Area of Study

1.6.1 Location

Lesotho is completely bordered and landlocked by South Africa (Maro, 2011). It is situated in the Eastern part of Southern Africa between latitudes 28° and 31° South and longitudes 27° and 30° East (Moeletsi and Walker, 2013; Moshoeshoe-Chadzingwa, 2007). Figure 1 displays Lesotho map.

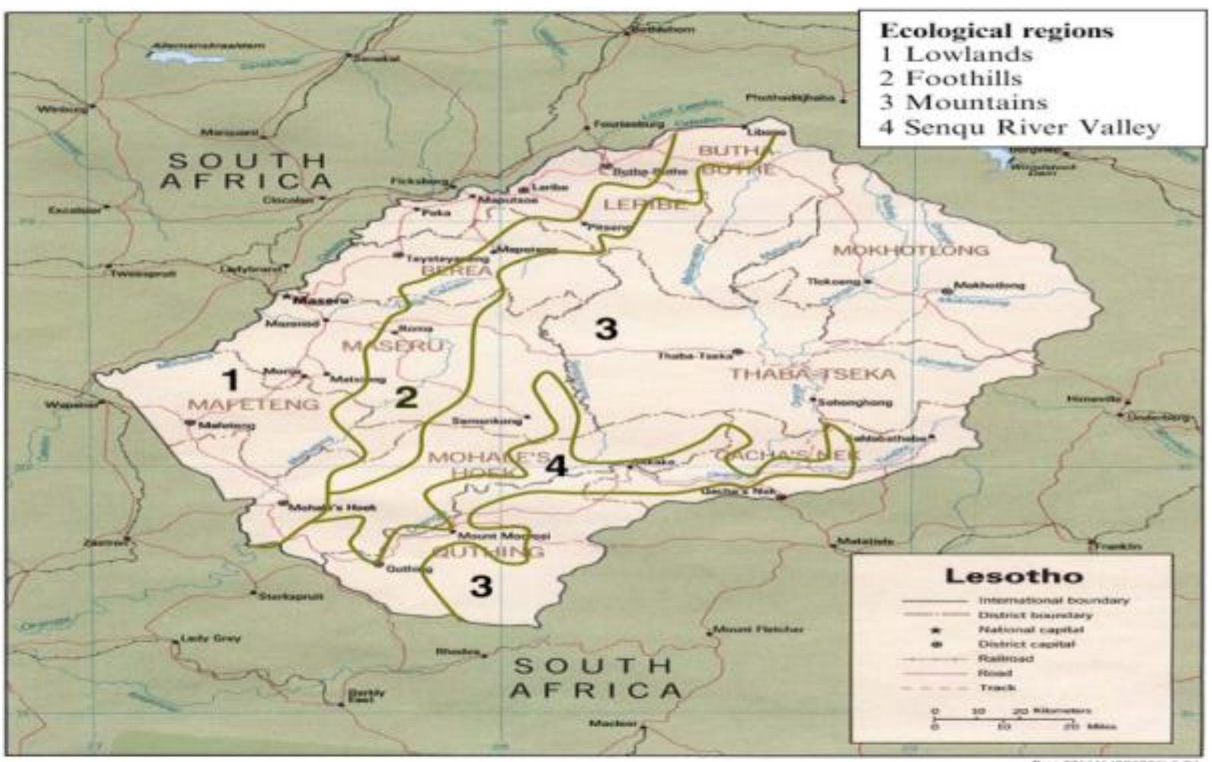


Figure 1: Map of Lesotho showing the ten administrative districts and the four Agro-ecological zones. Source: (Maro, 2011)

The country's altitude ranges from 1400m to 3480m above mean sea level (Moshoeshoe-Chadzingwa, 2007). Lesotho is estimated to have an area of 30,355 km^2 (Lesotho Meteorological Services, 2000), of which 60% is covered by rangelands, 31% by steep hills and mountains, while the arable land covers 9% of the landmass (Nhemachena *et al.*, 2017). The arable land is prone to severe soil erosion. About 40 million tonnes of soil is estimated to be eroded every year. (Lesotho Meteorological Services, 2000).

The country has ten districts that is: Butha-Buthe, Mafeteng, Leribe, Thaba-Tseka, Maseru, Mohale's Hoek, Mokhotlong, Qacha's Nek, Quthing and Berea (Moeletsi and Walker, 2013; Moshoeshoe-Chadzingwa, 2007). Four of these districts including Butha-Buthe, Thaba-Tseka, Leribe and Mohale's Hoek representing the four agro-ecological regions of the country were considered in this study. The four agro-ecological regions comprise the Foothills, the Senqu River Valley, the lowlands and the Mountains (Maro, 2011). Butha-Buthe and Leribe are the lowlands, foothills and mountains, whereas Thaba-Tseka are Mountains and Senqu River Valley. Mohale's Hoek represents the Senqu River valley, the lowlands, the mountains and the foothills (Bureau of Statistics, 2017).

The country's population is estimated to be 2 million, of whom 76% live in rural areas (Silici, 2010).

1.6.1.1 The Lowlands

The lowlands occupy roughly 5,200 km² representing 17% of the total surface area. The region covers the western part of Lesotho which lies between 1,400 m and 1,800 m (Lesotho Meteorological Services, 2000). The southern lowlands have infertile soils and experience low rainfall whereas the northern and central lowlands are categorized by fertile soils (Lesotho Meteorological Services, 2007; WFP, 2006).

1.6.1.2 The Senqu River Valley

The Senqu River valley covers 9% of the total land area (Maro, 2011). It is a narrow piece of land that margins the Senqu River banks and enters deep into the mountains, getting to the lower parts of the central tributaries of the Senqu river (Lesotho Meteorological Services, 2000). The soils along the valley varies from fertile to unfertile which makes this region the most unproductive in the Kingdom of Lesotho (Lesotho Meteorological Services, 2007; WFP, 2006).

1.6.1.3 The Foothills

The foothills constitute the region between the highlands and the lowlands. It covers about 4,600 km² representing 15% of the total land area. This region lies between 1,800 m and 2,000 m above mean sea level (Maro, 2011). The foothills are characterized by rich soils, making it suitable for agricultural production (Lesotho Meteorological Services, 2007; WFP, 2006).

1.6.1.4 The highlands

The highlands are dominated by the ecological area known as the Maluti Mountains, with elevation of 2000 to 3400 m. The region is about 18,047 km², representing 59 % of the total land area (Maro, 2011). It is separated by the Senqu River streams and trenches in a north-south orientation. The drainage system formed by deep river valleys makes living very challenging in this region. The mountain area is the main livestock grazing zone in the country (Lesotho Meteorological Services, 2007; WFP, 2006).

1.6.2 Soils

Generally Lesotho has thin soils. The underlying impervious rock causes the soil to have low water holding capacity, runoff and soil destruction as well as leaching of soil nutrients during high rainfall intensity (WFP, 2006). Most important soil groups of Lesotho are Mollisols and Alfisols (Mosenene, 1999; Schmitz and Rooyani, 1987).

Mollisols cover roughly 1.5 million hectares, representing almost half of the country's landmass (Schmitz and Rooyani, 1987). This soil type is suitable for agriculture production. It covers practically all the mountains slopes and mountain gorges as well as most of the foothills, the lowlands and Senqu river valley of Lesotho. They are dark coloured soils formed from basaltic parent material under the tall grass and natural vegetation in the mountains (Schmitz and Rooyani, 1987). Mollisols are moderately deep loamy textured soils which are productive (Mosenene, 1999).

Alfisols cover approximately 300,000 hectares of Lesotho. Alfisols are mostly found in the foothills and the lowlands of the country. They are grouped into two broad categories: duplex and the reddish soils. Duplex soils are extremely susceptible to gully erosion while reddish

Alfisols are intensively used for cropping (Schmitz and Rooyani, 1987). This soil type is characterized by a granular top layer with fine clay (Mosenene, 1999).

1.6.3 Climate

Lesotho's climate is classified as temperate continental, with features that can allow quite favorable economic activities. The country's climate is controlled by the latitudinal position in the subtropics under the global high-pressure belt 30° (Lesotho Meteorological Services, 2017). The country experiences four distinct seasons, namely, Winter (June, July, August), Autumn (March, April, May), Spring (September, October, November) and Summer (December, January, February) (Nhlapo, 2017). Temperature is generally high and fluctuating, while rainfall is erratic (Lesotho Meteorological Services, 2013). Summers are hot and moist, whereas winters are dry and cold. Winters are characterized by clear skies and dry air caused by the influence of prevailing high-pressure systems. Temperatures are warm to moderate throughout the day and cold immediately at dusk (Lesotho Meteorological Services, 2017).

1.6.3.1 Precipitation

Precipitation in Lesotho occurs as sleet, hail, snow as well as rain and is mainly influenced by natural features and absence of oceanic effect (Dejene *et al*., 2011). Rainfall is highly variable, within and between the seasons (Lesotho Meteorological Services, 2013). Precipitation varies from 500 mm to 1,200 mm annually (Lesotho Meteorological Services, 2000).

The rainy season is in summer beginning in October and ending in April. The highest rainfall amount is recorded in December, January and February months, where most areas in the country receive above 100mm each month. This frequently leads to flooding causing economic losses and other negative social and ecological impacts (Lesotho Meteorological Services, 2013). In winter, precipitation received is very low if any, and mostly occurs as snow in the mountains and sometimes in other parts of the lowlands. Snow is common in May to September. Normally, heavy snowfalls occur at the start or end of winter season. This always make rural living more challenging because people cannot access basic facilities (Lesotho Meteorological Services, 2013).

1.6.3.2 Temperature

Temperature in Lesotho is inconsistent on daily, monthly and yearly basis, and are usually lesser as compared to other places of same latitude. Annual mean temperature for the lowlands is 15.2 °C while for the mountains is 7 °C. The high altitudes experience the highest mean maximum temperatures of 20 °C whereas the lowlands experience 32 °C in January in all parts of the country. The mean minimum temperature of -3 degrees Celsius to -1 degrees Celsius are recorded for the lowlands and -8.5 degrees Celsius to -6 degrees Celsius for the mountains monthly.

In winter monthly minimum temperatures are -6.3 °C for mountains and 5.1 °C for lowlands area. Mean monthly minimum temperature of -10.7 °C can be recorded in extreme cases during winter, and daily minimum temperatures of -21 °C can be experienced (Lesotho Meteorological Services, 2013). June is the coldest month hence lowest temperature of 0 °C is regular.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of literature on the impacts of climate variability and change on sorghum production; the influence of climate parameters on sorghum yields; overview of the Aquacrop model; performance of General Circulation Models; impact of future climate on sorghum production; importance and agro-ecological requirements of sorghum crop; and sorghum growth and development stages. The chapter also presents the conceptual framework of this study.

2.2 Climate Variability and Change impacts on Sorghum Yields

Climate variability accounts for the observed temporal and spatial variability in agricultural productivity by influencing the development and growth of the crops and pastures. Rainfall variability is the main climatic constraint to agricultural productivity (WMO, 2010; de Louis et al., 2011; Ghaedi and Shojaian, 2020). Malebajoa (2010) assessed climate change impacts on crop yields using crop simulations and climate models in the lowlands of Lesotho, using climate data from 1970 to 2008. The rising trend in mean minimum and maximum temperatures and rainfall exerted a significant impact on yields of crops at Leribe and Maseru and an insignificant effect on yields of crops at Mohale's Hoek district.

Nhlapo (2017) investigated the relationship between temperature trends and altitude at different time scales in Lesotho using linear regression technique for two periods, 1931-2013 and 1968-2013. The warming trend for maximum and minimum temperature that varied over temporal scales over the study area, negatively impacted agriculture production in the lowlands of Lesotho, while at the same time benefiting the mountain areas as this will increase frost free days and the heat units. Sekoli and Morojele (2016) while studying sorghum production trends in Lesotho for period 1960 to 2013 revealed that sorghum yields were declining over the study period owing to the reduction of production area as well as the subsistence nature of sorghum farming in the country.

Seasonal and annual precipitation concentration index (PCI) values greater than 16 were obtained from 2001-2010 from 1981 to 2010 in several agro-climatic regions of Andhra Pradesh in India, with clear indications of changing rainfall patterns (Valli *et al*., 2013). Ezenwaji *et al.* (2017) used precipitation concentration index annually and seasonally for the period 1976-2013 to evaluate rainfall variability and distribution in Awka, Nigeria. The study revealed uniform rainfall distribution during the wet season with 87 % out of 38 years showing uniform rainfall distribution.

Shah *et al*. (2012) used Mann-Kendall statistical test to look at trends and variability of climate parameters for a period of 30 years (1981-2010) in Pakistan, Peshawar district, in which a decreasing rainfall trend and increasing mean and minimum temperatures trends were observed, whereas maximum temperature showed an unchanging trend. Yadav *et al*. (2014) looked at temperature and rainfall trends for 41 and 37 years respectively using the Sen's Slope Estimator and Mann-Kendall test for thirteen Uttarakhand districts of India. The results indicated that in several districts of Uttarakhand annual rainfall trend was increasing and a decreasing trend for maximum temperature but found an increasing trend for minimum temperature for all districts.

Kuri *et al*. (2014) studied the trends of precipitation and temperature as well as their influence on rice yield using the coefficient of variation (CV), linear trend model and linear regression model in Mymensingh district of Bangladesh for period 1975 to 2012. The findings indicated that the trend for maximum temperature and average annual rainfall was decreasing while minimum annual temperature and mean annual temperature showed a rising trend.

The study conducted by Bosire *et al*. (2019) analyzed climate variability and trends and the likely consequence on crop production in the semi-Arid environment of Machakos County in Kenya for the period 1981 to 2013 for MAM and OND seasons. This revealed less variability for temperature and a warming trend for minimum and maximum temperature on seasonal and annual time scales. However, high rainfall variability was observed for MAM and OND rainy seasons, and a decreasing annual rainfall trend.

Botai *et al*. (2018) studied spatial distribution of temporal rainfall in South Africa using precipitation concentration index yearly, supra-season and seasonal scale for the period 1998-2015. The results indicated that most parts of the country were characterized by low to moderate precipitation concentration.

A characterization of agro-climatology of Lesotho using rainfall and temperature data revealed that there was less variability for mean monthly minimum temperature and rainfall in Lesotho as well as the spatial variability for maximum temperature on year to year basis (Moeletsi, 2004). This study also revealed that seasonal rainfall varies across the country.

2.3 Influence of Climatic Parameters on Sorghum Yields

Water and temperature are essential elements for crop processes and responses such as molecular, biochemical and physiological processes, which in turn affect crop quality and yield (Prasad and Staggenborg., 2008). Grossi *et al*. (2015) examined sorghum yield sensitiveness to separate climate parameters in Brazil, Minas Gerais State. The results indicated that amongst other weather elements, sorghum yield was mostly influenced by precipitation, solar emission and atmospheric carbon dioxide concentration.

The research by Ibrahim (2015) on analysis of precipitation in yields of sorghum crop and sesame studied in Sudan for the period 2001 to 2010 used Fisher Integral Model, Chebyshev Orthogonal Polynomial and stepwise regression to show that rainfall was the main factor influencing crop yield in Sudan compared to temperature.

The negative trend on annual rainfall in four out of twelve locations and a positive trend in eight stations from 1975-2003 indicated that the May and June rainfall greatly influenced sorghum productivity (Bewket, 2009). The observed inter-annual and seasonal rainfall variability accounted for the marked variability in sorghum yields. In related studies, Alemayehu and Bewket (2016) studying the influence of climate variability based on monthly, seasonal and annual scales in Central highlands of Ethiopia on different crops including sorghum revealed high sorghum yields variability on year to year basis. Further, the study indicated that sorghum productivity was significantly correlated with rainfall received during August, a month associated with highest amounts of rainfall.

Similarly, Hudo (2016) evaluated the effect of climate variability and change on rain-fed sorghum yield in Sudan, Gadaref region based on temperature and rainfall data for 1961 to 2014, in which a significant positive relationship between sorghum yields and rainfall was found, while sorghum and temperature showed a significant negative relationship.

2.4 Crop Modelling

Climate Models are most important tools developed by several modelling scientists all over the world (Kamworapan and Surussavadee, 2019; Ramirez-Villegas and Jarvis, 2010). GCMs are used for climate projections and simulations globally (Ahmed *et al.*, 2019). The GCMs are accessible for a series of future possible emission scenarios called representative concentration pathways (RCPs). Many GCMs performs differently for various locations and vary in spatial resolution because of different weather patterns experienced in different locations.

Agricultural crop models are instruments used for research investigation and decision making, these include Decision Support System of AgroTechnology Transfer (DSSAT), Cropping Systems Model (CROPSyst) and World Food Studies crop growth model (WOFOST). Amongst these groups of agricultural models is AquaCrop, this new model is established by land and water division of Food and Agriculture Organization of the United Nations (Raes *et al.*, 2009; Steduto *et al.*, 2009). The model is developed to mimic crop response to the environmental conditions (Raes, 2017).

AquaCrop can be used in a wide range of herbaceous crops (Steduto *et al.*, 2009). This model is chosen for the use in this study because it is user friendly and requires less input information than other crop models. AquaCrop can also be used to simulate crop response under rain-fed and irrigated agriculture. According to Todorovic *et al*. (2009) the model can be useful across different climates, seasons as well as various locations.

2.4.1 Overview of AquaCrop Model

The AquaCrop model was established to address food safety as well as assessing the influence of environment and management on production of crops (Raes *et al*., 2009; Steduto *et al*., 2009). This is the crop simulation model that explains the relationship among soil and plants (Raes, 2017). AquaCrop shows yield responses to water deficit of herbaceous plants. The use of this model is suitable when addressing environments where water is the most controlling element in production of crops. The model seeks the balance among reliability, clarity and precision.

2.4.2 Data required by AquaCrop

This multi-crop water model requires a few number of unambiguous parameters and input variables (Raes *et al*., 2009). The AquaCrop model has four modules; climate, crop, soil and management practices. The agro-climatic data required include precipitation, minimum and maximum temperature and evapotranspiration (ETo) as well as Carbon dioxide (CO_2) concentration. These data can be daily, 10-day as well as monthly. The crop module of this model consists of development, growth and yield formation stages, whereas the soil component comprises the soil profile and ground water table (Raes *et al*., 2009). The management component includes agronomic practices such as irrigation and field management, as well as fertilization and use of bands. The sub model components of the AquaCrop model are presented in Figure 2.

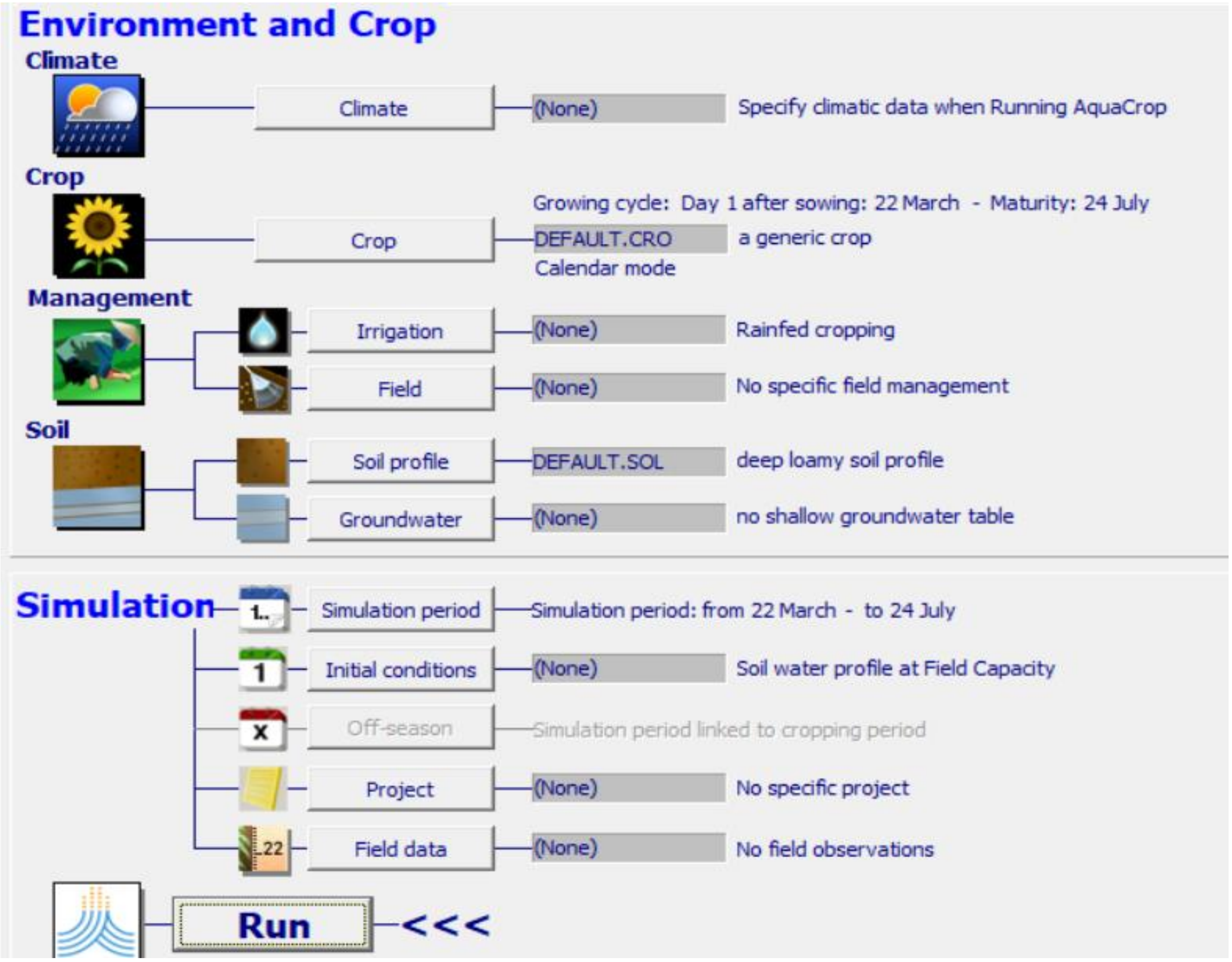


Figure 2: Sub model components of AquaCrop model (source : Raes *et al.*, 2009)

2.4.3 Assessing Suitability of AquaCrop Model on Different Crops

The AquaCrop model was evaluated for forecasting bean yields under varying amounts of irrigation water from 2015 to 2016 for the agrometeorological environments of Northeastern Brazil in humid tropical climate (Magalhães *et al*., 2019). The model performance was evaluated using Willmott's Index of agreement (d), RMSE and correlation coefficient (r) as well as the percentage deviation (D). The results indicated that observed and simulated values for a number of parameters including yield and estimated increased biomass and grain yield were more efficient in irrigated system without water shortage.

AquaCrop model performance was evaluated by Silva *et al.* (2017) using soybean planted under varied levels of water in both irrigated and rainfed farming systems in a humid climate for the dry period of June to October 2014 and for the wet season from November 2013 to March 2015 in Brazil. The model accuracy was evaluated using prediction error, MAE, coefficient of determination, Nash-Sutcliffe Efficiency Index, Willmott's index and RMSEN. The results revealed that the model was more effective under irrigated conditions than rainfed conditions.

Hudo (2016) used Aquacrop model to assess the influence of the changing climate on sorghum yields in Gadaref Area. The results showed declining sorghum yields in 2017- 2046. This was attributed to increasing temperature and decreasing rainfall. Mibulo and Kiggundu (2018) assessed the AquaCrop model for simulating growth and yields of maize under the rainfed conditions in Uganda for 3 seasons, namely, SOND in 2014 and MAMJJ and SOND in 2015. Model performance was evaluated using RMSE and Nash-Sutcliffe (E). The outcomes revealed that the AquaCrop model was able to simulate maize yield as well as growth effectively.

2.5 Performance of GCM models

Maher *et al.* (2018) compared CMIP5 and CMIP3 GCMs in Western Himalayan Region. The results revealed that CMIP5 GCMs simulated observed rainfall better than CMIP3 GCMs. They further concluded that CMIP5 GCMs were capable of replicating the inter-annual rainfall variability in an accurate way than the CMIP3 based GCMs.

Bosire *et al.* (2019) used 2 metrics that included modified index of agreement and RMSE to evaluate the performance of CanESM2, NorESM1-M, MIROC5, GFDL-ESM2M, MPI-ESM-LR, EC- EARTH, as well as the CNRM-CM5 models, and the ensemble from CORDEX under RCP 8.5 and RCP 4.5 to project temperature and rainfall for Machakos in Kenya. The results indicated that GFDL-ESM2M, CanESM2, NorESM1-M models and the ensemble performed well in simulating the observed climate.

While studying 15 GCMs from the World Climate Research Program (WCRP's) Coupled Model Intercomparison Project Phase 3 (CMIP3) for the period 2046-2065 and 2050-2099 using SRES A2 scenario, Dejene *et al*. (2011) indicated that Lesotho will experience an increasing temperature of 2.0 ºC to 2.5ºC for the period 2046-2065, and 3.5 ºC to 4.0 ºC for 2080-2099. It was further shown that rainfall variations in Lesotho seemed not to be clear as different models revealed wetting while others indicated drying conditions for the rainy season. The April to September season was projected to experience varying degrees of drying due to declining rainfall.

Malebajoa (2010) assessed performance of 4 GCMs including UKHADCM3, GFDL, CCCMA, and GISS-EH for A2 and B2 emission scenarios for 2030-2050 and 2080-2100 in Lesotho. The findings indicated that GFDL and UKHADCM3 models were more suitable as compared to other models in simulating future climate scenarios. Furthermore, it was observed that precipitation and temperature were highly overestimated by GISS-EH and CCCMA compared to the projections by GFDL and UKHADCM3. On the other hand, Lesotho Meteorological Services assessed the performance of 6 GCMs, namely, UKHI, CCCM, GFDL, OSU, GISS and UKTR while developing climate change scenarios for Lesotho for 2030, 2050 and 2075 using data from 1961 to 1990. The assessment identified GFDL and UKHI GCMs as superior models compared with CCCM, OSU, GISS and UKTR (Lesotho Meteorological Services, 2000). Further, these models projected increasing temperature and declining rainfall over Lesotho.

2.6 Impact of Future Climate Change on Sorghum Production

A number of studies have assessed the potential effects of climate change on sorghum production. Zewdu *et al.* (2020) evaluated the impact of the changing climate on selected sorghum varieties using estimated future climate scenarios for 2040-2069 and 2070-2099 under RCP 4.5 and RCP 8.5 using 20 global climate models for IPCC-AR5 in the Eastern region of Ethiopia. The results revealed future climate will negatively impact sorghum yield. Four downscaled GCM’s from the IPPC AR4 report revealed a projected rise in temperature while rainfall was projected to decline by 2050 in Lesotho (Gwimbi *et al*., 2013). It was further outlined that sorghum yields due to its ability to tolerate drought could increase.

Bosire *et al*. (2018) used the APSIM model to assess the influence of future climate on sorghum production at Machakos County for 2010-2039, 2040-2069 and 2070-2099 periods using CanESM2, NorESM1-M, GFDL-ESM2M and the ensemble under RCP 8.5 and RCP 4.5. The results indicated that all the GCMs projected an increase in sorghum yield for both OND and MAM growing seasons. In addition, it was revealed that projected rise in temperature and precipitation will create a beneficial environment for growth, development and productivity of sorghum crop in the county.

In a related study, Malebajoa, (2010) investigated the impact of climate change impact on the yields of sorghum, wheat and maize in the lowlands of Lesotho for the period 2030-2050 and 2080-2100 using the CROPWAT model and CCCMA, GFDL, GISS-EH and UKHADCM3 under A2 and B2 SRES emission scenarios. All the models studied projected a decrease in sorghum yield. Further, the models projected rising temperature and declining precipitation in Lesotho under future climate.

2.7 Importance and Agro-ecological requirements for Sorghum Production

2.7.1 Importance of Sorghum

Sorghum (*Sorghum bicolor* (L) Moench) is a vital main food crop in Africa. It is indigenous to Africa and it is the most adaptable crop to changing environmental conditions including climate change. Sorghum bicolor is the fifth most essential cereal crop after rice, wheat, maize, and barley (FAO, 2006; Department of Agriculture, Forestry and Fisheries, 2010). It is the key food grain crop for more than 750 million population living in Latin America, Asia and the semi-arid tropics of Africa (Department of Agriculture, Forestry and Fisheries, 2010). All over the world sorghum grain is used to feed human beings and animals, notably people living in the dry regions of Africa and India (Laidlaw and Godwin, 2008). Sorghum stems are used to extract sugar, while the grain can also be used in the processes for producing alcoholic drinks. The stover can be used for making decomposable packaging materials, inks and glues (WMO, 2010).

In Lesotho, sorghum is used for preparing porridge, papa as well as malt (Mekbib *et al*., 2011; Sekoli and Morojele, 2016). However, its popularity is centered on its use in making traditional beer and porridge (Lesotho Meteorological Services, 2000). Basotho substitute maize with sorghum in their diet. Sorghum is a shorter season crop, taking 120-140 days to reach physiological maturity.

2.7.2 Agro-Ecological requirements of Sorghum Crop

The general agro-ecological requirements for production of sorghum crop in the context of climate and soil conditions are presented in the subsections that follow.

2.7.2.1 Climatic Requirements

Sorghum is regarded a drought tolerant crop known for its ability to thrive in conditions of limited soil moisture. High yields of sorghum in South Africa can be obtained under rainfall conditions amounting to 300 mm to 750 mm (Department of Agriculture, Forestry and Fisheries, 2010) that is effective (higher infiltration relative to runoff). High sorghum yields can be optimized if more than 55 % of soil moisture is accessible and retained in the rooting area of the soil profile during the growing period (WMO, 2010). Adequate soil moisture is very crucial for sorghum planting. Sorghum crop is more tolerant to temporary waterlogging conditions.

Sorghum is planted when the soil temperature is at least 15 °C, at a spacing of 10 cm between plants (Department of Agriculture, Forestry and Fisheries, 2010). Sorghum requires optimal temperatures range of 27 °C to 30 °C for optimum germination and growth. High temperatures above these cardinal temperature range could have dramatic influence on sorghum yield. On the other hand, low temperature below freezing may lead to crop dying (Gommes *et al*., 2010) due to the high sensitivity of the crop to frost. More than 80% of sorghum seed emerges within 10 to 12 days when temperature is 15 °C (Department of Agriculture, Forestry and Fisheries, 2010). For seed emergence, the cardinal minimum temperature varies from 8 °C to 10 °C with the optimum temperature varying from 32 °C to 35 °C. The upper limit/ maximum cardinal temperature for sorghum germination is 40 °C (Mavi and Tupper, 2004). According to Gommes *et al*. (2010), a minimum temperature of 16 °C is essential for all the plant's functional developments to take place.

Solar radiation, a principal source of the requisite photosynthetically active radiation (PAR) is crucial for high grain yield formation. Sorghum crop does not grow well under shaded conditions.

2.7.2.2 Soil Requirements

For optimal crop production, sorghum grows well in soils of between 10 and 30 percent clay content. It does not grow well on sandy soil, unless the subsoil has heavy texture (Department of Agriculture, Forestry and Fisheries, 2010). Sorghum tolerates alkaline salts than other cereal crops and for that reason the crop can be cultivated productively on soil pH of 5.5 to 8.5. As compared to maize, sorghum tolerates short periods of waterlogging (Department of Agriculture, Forestry and Fisheries, 2010).

2.8 Sorghum Growth and Development Stages

Grain sorghum has nine different growth stages that characterize the crop's life cycle. According to the categorization by Vanderlip (1993), the developmental stages begin from 0, the emergence stage to 9, the maturity stage as presented in Table 1.

Table 1: Grain Sorghum Growth and Development Stages

Growth Stage	Days After Emergency	Plant characteristics and requirements
Stage 0	0	**Emergence stage.** Coleoptile noticeable at soil surface
Stage 1	10	**3-leaf stage**. The 1st, 2nd and 3rd collar leaves are visible. Growth and development depend on air temperature.
Stage 2	20	**5-leaf stage**. 5th collar leaf becomes visible. The rooting system and all plant parts develop fast. The coleoptile may fall.
Stage 3	30	**Growing point differentiation.** New leaves keep on growing. The stalk grows fast. Nutrient uptake increases as head growth begins.
Stage 4	40	**Final leaf visible in whorl**. Flag leaf is visible. The head growth continues. Water and nutrients uptake increases.
Stage 5	50	**Booting stage**– Panicle growth is completely attained. Light interception is maximized. The head attains full size and is now surrounded by flag leaf cover.
Stage 6	60	**Half-bloom stage**. The fast growing peduncle pushes the head through the flag leaf sheath.
Stage 7	70	**Soft dough stage**. Grain filling continues, accumulating almost half of its final dry mass. Older leaves continue to fall off.
Stage 8	85	**Hard dough**. 75% of final dry weight is accumulated. Plant no longer taking up nutrient. Less moisture is needed.
Stage 9	95	**Physiological maturity**. The black layer forms, which can be noticeable by a darkspot on the kernel near the embryo. Kernel moisture should vary between 25 to 35%. This depends on sorghum variety and growing environment.

Source: Vanderlip (1993)

2.9 Identified gaps

In view of the foregoing literature reviews, the major gaps that this study identified and attempted to bridge, based on the challenges facing sorghum farmers in Lesotho was inadequate knowledge and information on climate variability and change impact on crop production in Lesotho.

2.10 Conceptual Framework of the Study

The conceptual framework upon which this study was hinged, detailing study variables, their functional relationship and methods used in the study is presented in Figure 3.

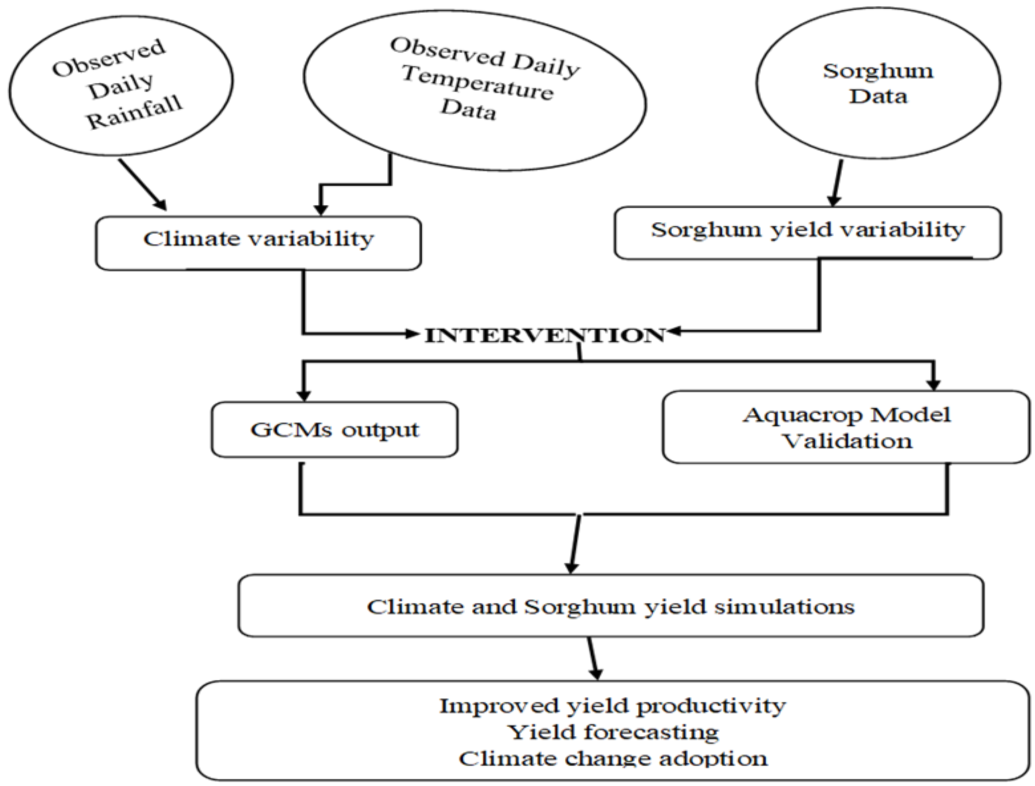


Figure 3: Conceptual Framework

The observed climate and sorghum yield data were used to establish the association amongst the two study parameters. This study focused on modelling the changing climate impacts on sorghum production using the AquaCrop model.

CHAPTER 3: DATA AND METHODOLOGY

3.1 Introduction

In this chapter, data and methods that were used to achieve the specific objectives set out in section 1.4 are presented. The first section of this chapter describes the type and sources of datasets that were used, while the second section describes various methods used to analyze the specific objectives of the study.

3.2 Types and Sources of Data

In this study, both observed and projected climatic data on rainfall and temperature, and sorghum yields were analyzed. Details of each set of data and their sources are described in the subsections that follow.

3.2.1 Climate Data

Observed daily rainfall and temperature data for the period 1986-2018 that were used in this study were obtained from the Lesotho Meteorology Services (LMS). Missing data in these data sets were filled using rainfall and temperature data that were sourced from the National Aeronautics and Space Administration (NASA) Prediction of world Energy Resources (Power) https://power.larc.nasa.gov/beta/data-access-viewer. The geographical coordinates and altitudes of the four stations that were used in this research are shown in Table 2.

Table 2: Coordinates and Elevation of the Meteorological Stations used in the Study

STATIONS	LONGITUDE	LATITUDE	ELEVATION (m)
Butha-Buthe	28.15°E	28.46ºS	1770
Leribe	28.03°E	28.53°S	1740
Mohale's Hoek	27.28°E	30.09°S	1620
Thaba-Tseka	28.35°E	29.33°S	2160

3.2.2 Crop Yield Data

The seasonal sorghum yield data (mt/ha) was collected from the Lesotho Bureau of Statistics (BoS) for a period of 19 years spanning the 1999/00-2017/18 cropping seasons.

3.2.3 Historical and Future Climate Data

Historical and future climate data for period 1986-2005 and 2030-2059 was sourced from the Climate System Analysis Group (CSAG) (https://cip.csag.uct.ac.za/webclient2/datasets/africa-merged-cmip5/). This study adopted the Representative Concentration Pathway (RCP) 4.5, representing the medium greenhouse gas emission scenario that is in line with the response measures being employed by Lesotho towards reducing GHGs emissions to project future climate. The downscaled future projections for monthly temperature and rainfall used in this research were based on 11 GCMs of the Coupled Model Intercomparison Project Phase 5 (CMIP5). Table 3 presents the CMIP5 Global Climate Models, names of institutions that developed the models and their respective countries.

Table 3: CMIP5 Global Climate Models used in the study

Global Climate Model	Institution	Country
CNRM-CM5	Centre National de Recherché Meteorologique (CNRM)-Centre Européen de Recherché et de Formation Avancée en Calcul Scientifique (CERFACS)	France
MIROC-ESM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	Japan
CanESM2	Canadian Centre for Climate Modeling and Analysis	Canada
FGOALS-s2	Atmospheric Sciences and Geophysical Fluid Dynamics/Institute of Atmospheric Physics, Chinese Academy of Sciences	China
BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University	China
MIROC5	Atmosphere and Ocean Research Institute The University of Tokyo, National Institute for Environmental Science and Japan Agency for Marine-Earth and Science and Technology	Japan
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory.	USA
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (University of Tokyo), and National Institute for Environmental Studies	Japan
MRI-CGCM3	Meteorological Research Institute	Japan
BCC-CSM1-1	Beijing Climate Center, China Meteorological Administration	China
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory.	USA

Source:(Kamworapan and Surussavadee, 2019)

3.2.4 Data Quality Control and Analysis

In order to address the numerous challenges inherent in weather data records associated with gaps and inconsistency arising from human or instrument error in printing and during data transmission, data quality checks were undertaken ahead of the analyses. The methods that were used for data quality control are described in the subsections that follow.

3.2.4.1 Estimation of Missing Data

All meteorological stations had missing data. Missing data were estimated using the correlation method. This method entailed determination of the correlation coefficient between the observed daily rainfall, daily maximum and minimum temperature data and the estimated satellite climate data sets from the National Aeronautics and Space Administration (NASA) Prediction of world Energy Resources (Power) (https://power.larc.nasa.gov/beta/data-access-viewer) and using this coefficient to convert the satellite estimated data into the observed data equivalent . The formula that was used is given in equation 1.

$$X = r_{XY} . y \qquad (1)$$

Where: X is the missing climate data, Y is climate data from National Aeronautics and Space Administration (NASA) Prediction of World Energy Resources (Power), r_{XY} is the correlation coefficient between satellite and observed climate data.

3.2.4.2 Testing for data Homogeneity

All the missing values were filled and data tested to check for homogeneity. The single mass curve technique was employed to test for data homogeneity. This method entailed cumulating the values of the study climatic parameters (rainfall, maximum and minimum temperature) and then plotting then against time. A resultant straight line plot indicated that the data was homogeneous, while a deviation from the straight line indicated heterogeneity of the data set. This inconsistency of data was corrected by multiplying the deviant data points with the ratio of the slopes of the two distinct lines expressed in the plots.

3.3 Methodology for Data Analysis

In this subsection methods that were used to analyze the specific objectives of this study are presented in the subsections that follow.

3.3.1 Determination of Variability in Climate and Sorghum Yields

The variability in the study for climate parameters and sorghum yields were computed using the coefficient of variation. In addition, the precipitation concentration index (PCI) was also used to determine the variability and distribution of rainfall. These methodologies are defined in the subsequent subsections.

3.3.1.1 Coefficient of Variation

Equation 2 gives the equation that was used to compute the coefficient of variation, expressed as percentage that gave a measure of how the data points for the study variable varied from the mean value.

$$CV = \frac{S}{\bar{X}} \times 100 \quad \text{..} \quad (2)$$

Where: CV is the coefficient of variation; $\bar{X}$ is the mean and S is the standard deviation.

The study adopted the classification criteria for coefficient of variation (CV) by Hare (1983), that categorizes CV values of <20 % as less variability; 20-30 % as moderate variability, and >30 % as high variability. These classifications were applied to the study variables (sorghum yield, temperature and rainfall).

3.3.1.2 Precipitation Concentration Index

This study adopted the Precipitation Concentration Index (PCI) methodology of Oliver (1980) in estimating the rainfall variability on seasonal time scales. The rainy season consisted of 7 months (October to April). Precipitation Concentration Index was calculated using equation 3, adopted from (Botai *et al*., 2018; Ezenwaji et al., 2017).

$$PCI_{Wet\ Seasonal} = \frac{\sum_{i=1}^{12} P_i^{2}}{(\sum_{i=1}^{7} P_i)^2} \times 58.3 \quad \text{..} \quad (3)$$

Where P_i the monthly rainfall amount in i^{th} month $\sum$ is summation over the 7 and 12 months

This study adopted the criteria by Oliver (1980) for categorizing PCI, that stipulates that:

a) PCI < 10, designates uniform rainfall distribution

b) PCI >11 and <15 designates moderate rainfall concentration

c) PCI >16 and < 20 designates irregular distribution

d) PCI > 20 designates a high rainfall distribution

3.3.1.3 Mann-Kendall Test

This study used the Mann-Kendall test statistic to determine the trends in the observed study variables. The test entails detection of a monotonic upward or downward trend in sequences of environmental and meteorological data (Pohlert, 2015) using equation 4.

$$s = \sum_{k-1}^{n-1} \sum_{j=k+1}^{n} sgn(X_J - X_k) \quad \text{...} \quad (4)$$

Where, S is the Mann-Kendall statistic, $X_J - X_k$ = time series observation in sequential order, n is the length of time sequence.

$$\text{With } sgn(x) = \begin{cases} +1 \text{ if } X > 0 \\ 0 \text{ if } X = 0 \\ -1 \text{ if } X < 0 \end{cases}$$

A positive value of S shows a constant rising trend in the data series whereas a negative value of S designates a declining trend.

The variance of the Mann-Kendall statistic was then computed using equation 5.

$$Var(S) = \frac{n(n-1)(2_n+5) - \sum_{i-1}^{m} t_i(i)(i-1)(2_i+5)}{18} \quad \text{........................} \quad (5)$$

Where t_i is number of data point to sample (i).

The test statistic Z that follows a normal standard distribution (Wagesho *et al*., 2013) was then computed using equation 6.

$$Z = \begin{cases} \dfrac{s-1}{\sqrt{Var(s)}}, if\ S > 0 \\ 0, \quad\quad if\ S = 0 \\ \dfrac{s+1}{\sqrt{Var(s)}}, if\ S < 0 \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

A positive Z indicated a rising trend while a negative Z show a declining trend. The null hypothesis $\boldsymbol{H_o}$ that was tested was that there is no trend over time. The alternative hypothesis, $\boldsymbol{H_1}$ was defined as having a decreasing or increasing trend over time period. H_o was rejected if $|\mathbf{Z}| \geq \mathbf{Z}_{(1-\alpha/2)}$ at $\alpha=0.05$.

3.3.2 Determination of the Relationship between Climate Parameters and Sorghum Yields

Both correlation and regression analyses were used sequentially to establish the relationship among climate elements (rainfall and temperature) and sorghum crop yields. These methods are described in the subsections that follow.

3.3.2.1 Correlation Analysis

Correlation measures the robustness of the association amongst two parameters. This analysis was done by computing the Pearson's correlation coefficient given by equation 7.

$$\boldsymbol{r_{XY}} = \frac{\sum_i^n (\boldsymbol{X}_i - \overline{\boldsymbol{X}})(\boldsymbol{Y}_i - \overline{\boldsymbol{Y}})^2}{\sqrt{\sum_i^n (\boldsymbol{X}_i - \overline{\boldsymbol{X}})^2 (\boldsymbol{Y}_i - \overline{\boldsymbol{Y}})^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Where: $\boldsymbol{r_{XY}}$ is the correlation coefficient, $\boldsymbol{X_i}$ is the climate variable, $\overline{\boldsymbol{X}}$ is the mean of the climate variables, Y_i is the sorghum yields, $\overline{\boldsymbol{Y}}$ = sorghum yields mean and n = number of data points.

The correlation coefficient obtained from equation 7 ranges from +1 and -1, where +1 signifies a perfect positive association between pairs of variables, while -1 indicates a perfect negative association. On the other hand, the value close to 0 indicates no association between study variables (Bewick *et al*., 2003).

The statistical significance of the correlation coefficients in equation 7 were tested using the student t-test based on the comparison between a computed t-statics given by equation 8 and a tabulated student t-value at (n-2) degrees of freedom at 5% significance level.

$$t_{(n-2)} = r\sqrt{\frac{(n-2)}{(1-r^2)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

Where: **r** is the correlation coefficient, n-2 degree of freedom whereas n is the sample size

The null hypothesis, H_o tested was that there was no significant correlation among climatic characteristics and yields of sorghum. The alternative hypothesis, H_1 was that there was a significant correlation amongst climatic characteristics and yields. The correlation coefficient was considered statistically significant when the t-value computed was greater than tabulated t.

3.3.2.2 Regression Analysis

The climatic variables that gave rise to statistically significant correlation coefficients with sorghum yields were regressed on sorghum yields to generate a linear regression equation of the form given in equation 9.

$$Y = a_o + a_1x_1 + a_2x_2 + \ldots + a_nx_n \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

Where Y is the dependent variable (sorghum yields), a_n is the coefficient of regression, $\mathbf{x_n}$ represents climate variables, a_o is the constant of regression (y-intercept).

3.3.3 Assessment of the Impact of Future Climate Variability and Change on Sorghum Production

The AquaCrop model was used to assess the impact of future climate variability and change on sorghum yield based on historical and projected climatic data. This model is driven by climate and crop data, as well as soil characteristics and management practices (Raes *et al*., 2009). The study first evaluated the suitability of the CIMP5 models in simulating future climate.

3.3.3.1 Evaluation of the performance of CMIP5 models

The suitability of CMIP5 models was evaluated by comparing the observed and historical climate data from the CMIP5 models for the period 1986/1987 to 2004/2005 rainy seasons in order to identify the best performing model for adoption in simulating future climate. To maintain uniformity, the selection criteria for the best performing model was done based on the low rank value from the overall summation ranking and the appearance of GCMs in all the four districts with ranks 1 to 4.

Evaluation of the CMIP5 models performance was done using the Pearson's correlation coefficient (described in subsection 3.3.2) and the RMSE. The root mean square and model ranking methods are presented in the subsections that follow.

3.3.3.1.1 Root Mean Square Error

Root mean square error (RMSE) was used to evaluate the model performance by comparing the observed and simulated values using equation 10.

$$\boldsymbol{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \quad \text{...} \quad (10)$$

Where:

RMSE represents Root Mean Square Error,

P, the simulated value

O, the observed value

n, the number of observations and

i, the simulated and observed pairs.

3.3.3.1.2 Model Ranking

This study ranked the performance of the eleven (11) CMIP5 GCMs based on the ranking of their resultant correlation coefficient and RMSE using scores of 1 to 11 for each metric. A score one (1) was assigned to the GCM with the highest correlation coefficient and lowest RMSE value, and hence considered to be the best performing model. A score eleven was assigned to GCMs that gave rise to lowest correlation coefficients and highest RMSE values, and hence considered as the poorest performing models to be adopted for simulation purposes.

The ranks for correlation coefficient and RMSE for each of the study GCMs associated with rainfall, maximum and minimum temperature were summed up to get an overall summation that formed the basis for ranking performance of GCMs. The lowest values for overall rank summation were considered the best performing GCM's and were therefore used for impact analysis in this study. The highest ranking values indicated the worst performing models and were therefore not fit for simulating future climate in Lesotho.

3.3.3.2 AquaCrop Model Validation

The model was validated by comparing the observed and simulated sorghum yields based on the available data for 1999/2000 to 2017/2018 using the Pearson's correlation coefficient described in sub-section 3.3.2.

3.3.3.3 Future Sorghum Yield and Climate Projections

The future sorghum yield was predicted using future climate data for 2030/31 to 2059/60 relative to observed data of the base period 1999/00-2017/18. The percentage change in rainfall, temperature and sorghum yield was calculated as the difference between projected and base period data as given by equation 10.

$$\%\ \text{Change} = \frac{\text{Projected data} - \text{Historical average data}}{\text{Historical average data}} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents and discusses the results obtained from the analyses of the specific objectives based on different methods outlined in section 3.3.

4.1.1 Estimation of missing data

The four stations used in this study had missing data values of less than 10 % for both rainfall and temperature for the period of 1986 to 2018. There were no missing values for sorghum from the period 1999/00-2017/18. The missing values were estimated using correlation method. The data was further checked for consistency using the single mass curve.

4.1.2 Data homogeneity

Figures 4 to 6 present single mass curves of observed rainfall in Butha-Buthe, maximum temperature in Mohale's Hoek and Minimum temperature in Leribe for the period 1986-2018.

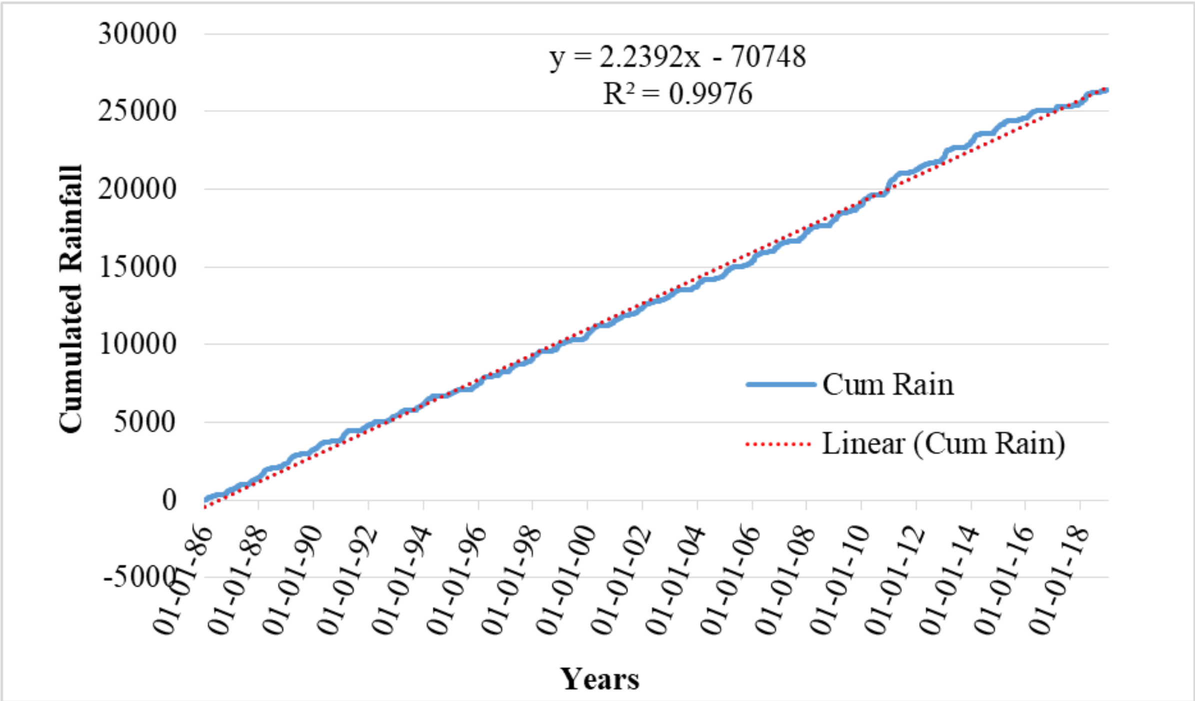


Figure 4: Single mass curve showing cumulative rainfall for Butha-Buthe from 1986-2018

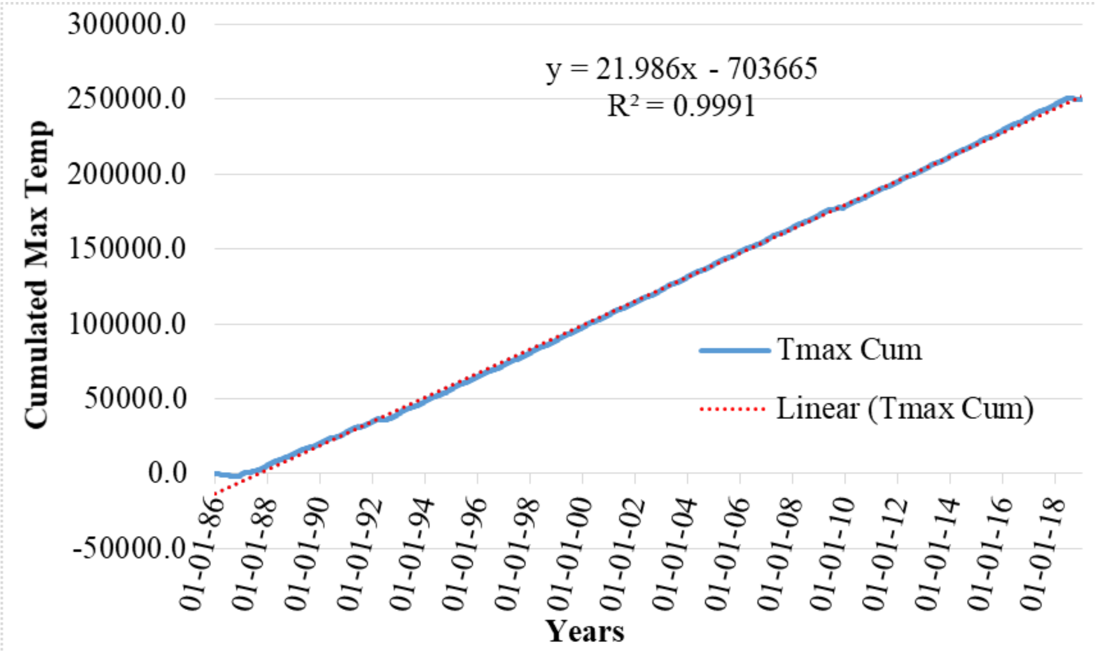


Figure 5: Single mass curve showing cumulative maximum temperature for Mohale's Hoek from 1986-2018

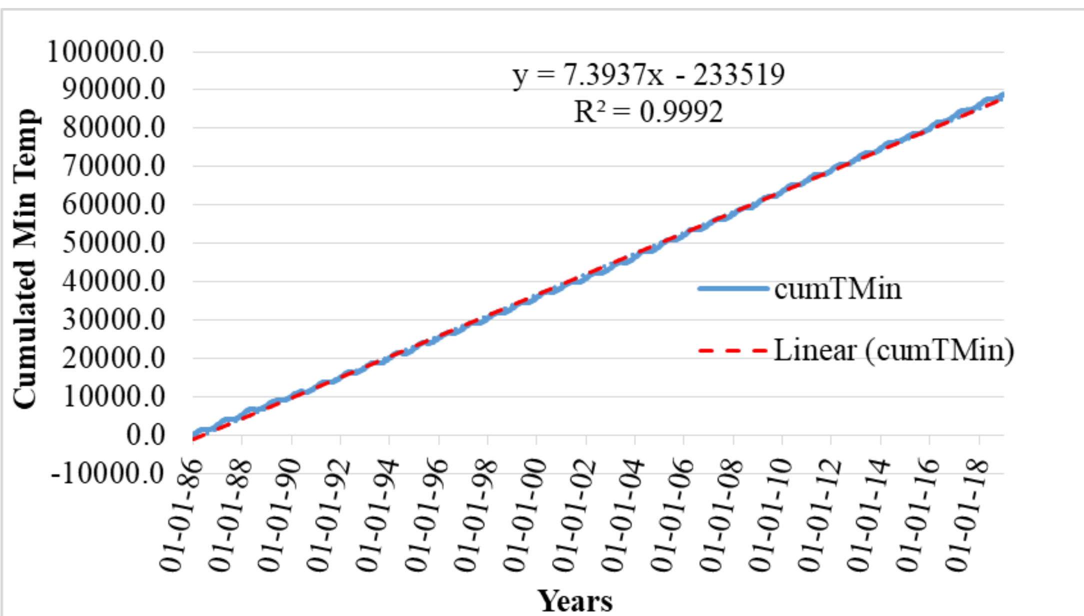


Figure 6: Single mass curve showing cumulative minimum temperature for Leribe from 1986-2018

These figures gave straight line plots, indicating that the data sets were homogeneous and hence suitable for use in the analysis of the study specific objectives.

4.2 Variability of Climatic Parameters

This section presents results for variability of monthly and seasonal rainfall, maximum temperature, and minimum temperature for the period 1986/87 to 2017/18 rainy seasons.

4.2.1 Variability of Monthly and Seasonal Rainfall

Table 4 shows the mean monthly and seasonal rainfall and their coefficients of variation from October to April for Butha-Buthe, Thaba-Tseka, Leribe and Mohale's Hoek stations for the period 1986/87-2017/18.

Table 4: Variation of Monthly and Seasonal Rainfall for Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek stations for the period 1986/87-2017/18

	October	November	December	January	February	March	April	Wet Season
Thaba-Tseka								
Mean	63	77	80	105.7	91.3	85	34.6	566.6
CV	63.8	52.1	56.8	48.3	51.7	65.1	65	23.5
Butha-Buthe								
Mean	75.4	93.7	110.2	140.2	120	105.3	58.5	703.3
CV	61.5	64.9	64.3	63.2	46.9	51.5	66.6	18.3
Leribe								
Mean	72.7	87.2	101.7	130.3	108	103.6	57.9	705.3
CV	66.7	58.2	54	60.1	58.8	59.8	63.1	22.9
Mohale's Hoek								
Mean	60.2	74.9	104.1	114.5	101.1	98.3	57.8	599.9
CV	83.6	69.5	56.2	53.7	63.3	56	78.6	24.4

Wet season: October, November, December, January, February, March and April; CV is the Coefficient of Variation

In January, mean monthly rainfall of above 100 mm was received for all the stations while below 60 mm was recorded in April. These findings agreed with those of Moeletsi (2004) which showed that mean monthly rainfall of above 100 mm was recorded in most parts of the country with a sudden decrease of less than 60 % in April. However, the highest amount of rainfall was recorded at Butha-Buthe (140.2 mm) and Leribe (130.3 mm). Mohale's Hoek and Thaba-Tseka recorded 114.5 mm and 105.7 mm respectively. These results also agree with those of Tongwane and Moeletsi (2015) which showed that Butha-Buthe and Leribe were receiving the highest mean monthly rainfall in January. This study, however, shows that the peak occurred in months of December to February.

All the four study stations during these months received on average 70 mm to over 100 mm of mean monthly rainfall. These months mark the onset of the wet period and corresponds with the sorghum cropping season. At this time, field preparation commences since sorghum production in Lesotho is purely rain-fed. The end of the wet period is marked by rapid decrease in rainfall in April where all the stations record below 60 mm. These results show high variability in monthly rainfall according to the criteria by Hare (1983) who categorized coefficients of variation greater than 30 % as highly variable.

From Table 4, the mean seasonal rainfall recorded at Butha-Buthe was 703.3 mm, Leribe recorded 705.3 mm while Mohale's Hoek and Thaba-Tseka recorded 599.9 mm and 566.6 mm respectively. These results agree with those by Moeletsi (2004) that indicated seasonal rainfall of more than 700mm received at Leribe and Butha-Buthe. On the other hand, the findings of this study disagree with those of Moeletsi (2004) who reported that Mohale's Hoek and Thaba-Tseka districts received less than 500mm.

Rainfall variability during the rainy season was moderately variable for Butha-Buthe (18.3%), Leribe (22.9%), Mohale's Hoek (24.4%) and Thaba-Tseka (23.5%). This indicates occurrence of reliable rainfall which would help farmers to undertake early land preparation, application of farmyard manure and sowing. These findings, however, disagree with those of Tongwane and Moeletsi (2015) that revealed high seasonal rainfall variability at Leribe (34%) and Butha-Buthe (47%). The difference could have been caused by the differences in years chosen for the studies.

Tongwane and Moeletsi (2015) observed that high variability in rainfall makes field operations including sowing quite challenging.

4.2.2 Variability of Monthly and Seasonal Temperature

Table 5 presents the coefficients of variations for monthly and seasonal maximum and minimum temperatures in Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek.

Table 5: Variation of Monthly and Seasonal Maximum and Minimum Temperature for Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek for 1986/87-2017/18

Maximum Temperature								
	October	November	December	January	February	March	April	Wet Season
Thaba-Tseka								
Mean	21.6	21.6	23.4	22.9	21.8	21.1	18.6	19.9
CV	10.4	10.9	7.8	10.7	16.6	8	10.5	9.8
Butha-Buthe								
Mean	23.3	24.5	25.6	26.4	25.6	24.6	22	25.1
CV	11	11.3	12.8	7.3	5.7	4.9	7.6	4.8
Leribe								
Mean	24.1	25.1	26.5	27.1	26.3	24.5	21.6	23.4
CV	4.9	6.9	6.3	6.4	6.9	6.3	8.8	9.3
Mohale's Hoek								
Mean	24.7	25.9	27	27.8	27.2	24.8	21.5	24.0
CV	9.7	7.1	9.7	7.2	7.3	9.7	10	6.9
Minimum Temperature								
	October	November	December	January	February	March	April	Wet Season
Thaba-Tseka								
Mean	7.2	8.5	10.1	10.9	10.1	9.1	5.8	6.7
CV	26.8	19.2	12.3	13	24	12.2	24.3	18.1
Butha-Buthe								
Mean	9.5	11	12.6	13.1	13.1	11	7.5	10.0
CV	14	13	13.4	21.3	14.4	16	17.8	9
Leribe								
Mean	9.3	11.2	13	14.1	13.5	11.4	7.5	11.7
CV	11	12.3	7.7	7	11	9.4	15.7	9.8
Mohale's Hoek								
Mean	9.6	11.8	13.3	14.4	13.9	12.1	8.3	9.2
CV	13.9	9	11.4	9.8	20.2	10.6	14.4	15.1

CV is the Coefficient of Variation; Wet season: (October, November, December, January, February, March and April)

The coefficient of variation for monthly maximum temperature ranged from 4.9 to 12.8 % in Butha-Buthe, 4.9 to 8.8 % in Leribe, 7.2 to 10 % in Mohale's Hoek and 7.8 to 16.6 % in Thaba-Tseka. Less to moderate variability was observed in Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek between the months of October to April. This implies occurrence of fairly uniform monthly temperature over the study area. These results are in agreement with those of Moeletsi (2004) who observed less variability of mean monthly maximum temperature over Lesotho. Based on Hare (1983) classification of coefficients of variation less than 20 % are classified as less variable while values greater than 20-30 % are categorized as moderate.

The highest average maximum temperature was noted in December, January and February months. The maximum value of 27.8 °C was recorded at Mohale's Hoek in January, followed by Leribe, Butha-Buthe and Thaba-Tseka with values of 27.1 °C, 26.4 °C and 22.9 °C respectively. The highest minimum temperature value of 14.4 °C was recorded at Mohale's Hoek in January, followed by Leribe, Butha-Buthe and Thaba-Tseka with values of 14.1 °C, 13.1 °C and 10.9 °C respectively.

With regard to the average seasonal maximum temperature, the values recorded during this period were 24.0 ºC at Mohale's Hoek, 23.4 ºC at Leribe while Butha-Buthe and Thaba-Tseka recorded 25.1 ºC and 19.9 °C respectively. The average seasonal minimum temperatures recorded ranged between 6.7 ºC to 11.7 °C. The observed temperatures were well over risky levels. Mavi and Tupper (2004) indicated that harmful temperatures to the sorghum crop during its development phases range from -2 to -3 degrees Celsius during germination phase, -1 to -2 degrees Celsius in flowering phase, and -2 to -3 degrees Celsius during the fruiting phase.

The coefficient of variation for maximum temperature range between 4.8 % and 9.8 %, while for minimum temperatures ranged between 9 % and 18.1 %. The less variability in seasonal maximum and minimum temperatures implies that both minimum and maximum temperatures are fairly uniform.

Temperature is the key element that affects sorghum growth and development as well as the grain quality and yield. Minimum temperature suitable for sorghum germination as attested by

Department of Agriculture, Forestry and Fisheries (2010) varies between 7 to 10 °C. In this study, minimum monthly temperatures varied between 7.2 and 14 °C at the start of the planting season in the months of October and November.

Sorghum crop requires stable maximum temperature from emergence stage to physiological maturity stage. High temperatures beyond the optimum level (40 ºC) favor disease and pests outbreaks. Under these temperatures, aphids which have serious effects on sorghum yield become common. A decrease in temperature below zero degrees is harmful to sorghum crop especially at its early stages of growth and during flowering stage. Sorghum germination and seedling establishment are sensitive to low temperature (WMO, 2010).

4.2.3 Seasonal Rainfall Distribution

Table 6 presents the proportion of years with PCI of below and above 16 for Leribe, Butha-Buthe, Mohale's Hoek and Thaba-Tseka for 1986/87-2017/18.

Table 6: Number of Years and Percentage Number of Years with (PCI<16) and (PCI>16) for Leribe, Butha-Buthe, Thaba-Tseka and Mohale's Hoek for 1986/87-2017/18

Stations	Number of years (PCI<16)	% Number of years (PCI<16)	Number of years (PCI>16)	% Number of years (PCI>16)
Leribe	32	97	1	3
Butha-Buthe	32	97	1	3
Thaba-Tseka	31	94	2	6
Mohale's Hoek	31	94	2	6

PCI<16 uniform to moderate distribution   PCI>16 irregular to strongly irregular distribution

At Butha-Buthe and Leribe, 97% of the years show uniform to moderate rainfall concentration while 3% of the years are characterized by irregular to strongly irregular distributions. At Mohale's Hoek and Thaba-Tseka, 94% of the years depicted uniform to moderate precipitation concentration indices, while 6% of the years indicated irregular to strongly irregular rainfall concentration. This means that all the months of the wet seasons received almost equal amount of rainfall. This results are in agreement with those of Ezenwaji *et al*. (2017) who showed uniform distribution of rainfall during the wet period.

The higher PCI values indicate high variability of the monthly precipitation of a locality. From these results it can be concluded that most of the months received equal rainfall amount in all the locations. The number of years with PCI<16 were more than the number of years with PCI>16. At Butha-Buthe and Leribe, 32 years out of 33 years had PCI<16 while only 1 year has PCI>16. In Mohale's Hoek and Thaba-Tseka, 31 years had PCI<16 whereas 2 years had PCI>16.

4.2.4 Seasonal Rainfall, Maximum and Minimum Temperature Trends

Table 7 presents the Mann-Kendall's tau statistic depicting the observed trends in seasonal rainfall, maximum temperature, and minimum temperature for Butha-Buthe, Thaba-Tseka, Leribe and Mohale's Hoek for the period 1986/87 to 2017/18.

Table 7: Trends for Seasonal Rainfall, Maximum and Minimum Temperature for Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek

Station	Climate parameter	Kendall's Tau	p-value	Statistical Significance
Thaba-Tseka	Rainfall	0.11	0.36	Not significant
Butha-Buthe		0.13	0.30	Not significant
Leribe		0.13	0.30	Not significant
Mohale's Hoek		0.15	0.22	Not significant
Thaba-Tseka	Maximum Temperature	0.27	**0.03**	Significant
Butha-Buthe		0.05	0.70	Not significant
Leribe		-0.17	0.18	Not significant
Mohale's Hoek		0.5	**<0.0001**	Significant
Thaba-Tseka	Minimum Temperature	0.51	**<0.0001**	Significant
Butha-Buthe		0.33	**0.01**	Significant
Leribe		0.32	**0.01**	Significant
Mohale's Hoek		0.39	**0.00**	Significant

The bolded values are statistically significant at 95% confidence level

Table 7 shows that there was an insignificant increasing trend for rainfall at $p<0.05$ at Thaba-Tseka, Butha-Buthe, Leribe as well as at Mohale's Hoek. An increase in rainfall especially during the cropping season will improve sorghum production. Many studies have shown that rainfall is depicting decreasing trends in different locations (Kuri *et al*., 2014; Shah *et al*., 2012; Bosire *et al*., 2019). Lesotho relies mostly on rain-fed agriculture which is more vulnerable to climatic hazards than irrigated agriculture (Dejene *et al*., 2011).

The results for maximum temperature at Mohale's Hoek and Thaba-Tseka show statistically significant increasing trend because the p-values are less than the significant level $\alpha=0.05$ with positive tau values. An insignificant increasing trend was depicted at Butha-Buthe whereas a non-significant decreasing trend was detected at Leribe with a Kendall tau value of -0.17. This signifies an increasing maximum temperature trend at Mohale's Hoek, Butha-Buthe and Thaba-Tseka while Leribe depicted a decreasing trend.

From the Mann-Kendall test, tau values are positive and the p-values are less than $\alpha=0.05$ for minimum temperature in all the four areas of this study. This indicates that minimum temperature trend is significantly rising in all the locations. The results agrees with those of Malebajoa (2010) and Nhlapo (2017) that showed an increasing temperature trend in Lesotho. This increase in temperature would result in accumulation of growing degree days/heat units, increase the rate of photosynthesis that is beneficial to sorghum growth and development. An increase in the temperature, especially in the mountain areas of Lesotho, will be beneficial to sorghum crop as it would not suffer from the low temperature injury due to chilling, glaze, suffocation freezing as well as heaving.

4.2.5 Variability of Sorghum yield

Table 8 presents the coefficient of variation for sorghum yields for Butha-Buthe, Thaba-Tseka, Leribe and Mohale's Hoek for the period 1999/00-2017/18 cropping season.

Table 8: Variations on Sorghum Yield in Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek for 1999/00-2017/18 Cropping Season

Parameter	Thaba-Tseka	Butha-Buthe	Leribe	Mohale's Hoek
Mean (ton/ha)	0.72	0.54	0.80	0.55
CV (%)	87	50	103	43

The mean sorghum yield in Leribe is 0.8 ton/ha, while Thaba-Tseka, Mohale's Hoek and Butha-Buthe yielded 0.72 tons/ha, 0.55 tons/ha and 0.54 tons/ha respectively. The variability of sorghum yield is high over the study area. Mohale's Hoek had the coefficient of variation of 43 %, followed by Butha-Buthe with 50 %, Thaba-Tseka and Leribe had CV values of 87 % and 103 % respectively. High variability in sorghum yield could be attributed to challenges in agronomic practices, choice of the variety, as well as incidences of pests and diseases.

4.2.6 Trends in Sorghum yields

Figure 7 presents trends in the sorghum yields at the four study areas for a period of 1999/00 to 2017/18. There are insignificant negative yield trends for Butha-Buthe, Leribe and Thaba-Tseka districts and non-significant positive yield trends in Mohale's Hoek.

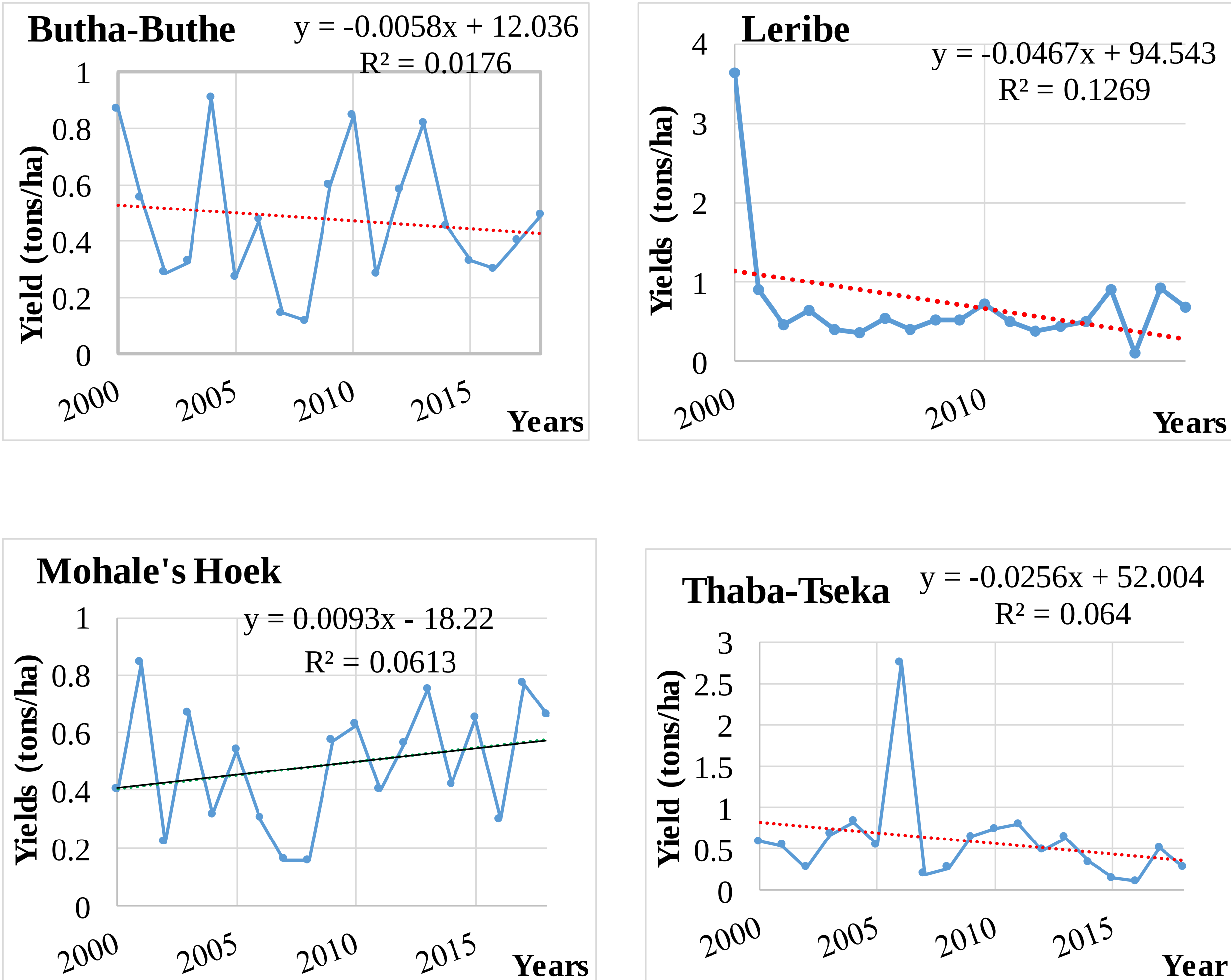


Figure 7: Trends for sorghum yield in Butha-Buthe, Mohale's Hoek, Leribe and Thaba-Tseka for the period 1999/00 -2017/18

Sorghum yield is increasing at the rate of 0.0093 tonnes per hectare per year in Mohale's Hoek. The degree of the decreasing trend is at the rate of 0.0058, 0.0467 and 0.0256 tonnes/ha/year for Butha-Buthe, Leribe and Thaba-Tseka respectively. This finding is in agreement with that of Sekoli and Morojele (2016) who observed a decreasing trend in sorghum yields in Lesotho

4.3 Relationship between Climatic Parameters and Sorghum Yields

This section presents the results for correlation and regression analyses that gave rise to the relationship between climatic parameters and sorghum yields in Leribe, Butha-Buthe, Thaba-Tseka and Mohale's Hoek.

4.3.1 Association between Climatic Parameters and Sorghum Yields

Table 9 presents the correlation coefficients between sorghum yield and each of seasonal rainfall, maximum temperature, and minimum temperature, as well as the computed t-statistic (T-calculated) for Butha-Buthe, Mohale's Hoek, Leribe and Thaba-Tseka based on data for 1999/00 to 2017/18.

Table 9: Correlation Coefficients between sorghum yield and rainfall, maximum temperature and minimum temperature for Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek

Station	Climate Parameters	Correlation Coefficient	T-calculated	Statistical significance
Thaba-Tseka	Rainfall (mm)	**0.47**	2.24	Significant
	Maximum Temperature (°C)	0.36	1.6	Not Significant
	Minimum Temperature(°C)	0.20	0.84	Not Significant
Butha-Buthe	Rainfall (mm)	**0.46**	2.14	Significant
	Maximum Temperature (°C)	**0.48**	2.28	Significant
	Minimum Temperature(°C)	0.34	1.5	Not Significant
Leribe	Rainfall (mm)	**0.49**	2.32	Significant
	Maximum Temperature (°C)	**0.46**	2.14	Significant
	Minimum Temperature(°C)	0.29	1.29	Not Significant
Mohale's Hoek	Rainfall (mm)	**0.45**	2.32	Significant
	Maximum Temperature (°C)	0.16	0.67	Not Significant
	Minimum Temperature(°C)	0.40	1.78	Not Significant

The bolded values are statistically significant at 95% confidence level of the student t-distribution whose critical value was t_{n-2}

The correlation coefficients between sorghum yields and rainfall were 0.47, 0.46, 0.49 and 0.45 at Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek respectively. These coefficients were statistically significant at 5% significance level, implying that sorghum yields increased with increasing rainfall amounts. These findings are in agreement with those of Malebajoa (2010) who stated positive, though insignificant correlation coefficients between rainfall and sorghum yields.

Maximum temperature positively correlated with sorghum yields at Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek. The correlation coefficients were statistically significant at 5% significance level at Butha-Buthe and Leribe, but were statistically insignificant at Mohale's Hoek and Thaba-Tseka. Minimum temperature gave rise to positive correlation coefficients with sorghum yields in all the study districts amounting to 0.20, 0.29, 0.40 and 0.34 in Thaba-Tseka, Leribe, Mohale's Hoek and Butha-Buthe respectively. However, though these correlation coefficients were not statistically significant at 5% significance level, increasing minimum temperature increases sorghum yields.

4.3.2 Regression analysis

Table 10 presents regression equations linking the climatic parameters that correlated significantly with sorghum yields in Butha-Buthe, Thaba-Tseka, Leribe and Mohale's Hoek districts.

Table 10: Regression equations linking sorghum and climate parameters for Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek

Districts	Regression Equation	Coefficient of determination (R^2)	F-Statistic	p- value
Thaba-Tseka	$Y= -0.6706 + 0.0024X_1$	0.23	5.5	0.04
Butha-Buthe	$Y= -2.77 + 0.00081X_1+ 0.1069X_2$	0.39	5.13	0.02
Leribe	$Y= -1.2084 + 0.0002X_1$	0.24	5.4	0.03
Mohale's Hoek	$Y= -0.2034 + 0.0012X_1$	0.20	4.35	0.05

Y is sorghum yield, X_1 is Rainfall (mm) and X_2 is Maximum Temperature (°C)

These findings show that rainfall and maximum temperature accountant for 39% of the variation in the yield of sorghum at Butha-Buthe district. This indicates that 61% of the variation in sorghum yields could possibly be explained by factors such as evapotranspiration, solar radiation and other factors such as an introduction of new agricultural technologies, crop management practices, crop variety and fertilizer use. Similar results were obtained by Malebajoa (2010) who reported a significant relationship between rainfall and crop yield. Rainfall accounted for lower variance of 24 %, 20 % and 23 % in sorghum yields at Leribe, Mohale's Hoek, and Thaba-Tseka respectively. This implies that sorghum yields in these districts are dependent on other climatic factors that were not considered in this study such as solar radiation, and evapotranspiration, as well as technological and crop management factors.

4.4 Impact of Future Climate Variability on Sorghum Production

This section presents the results of the suitability of the CMIP5 models in simulating future climate that formed a basis for examining the impact of future climate on sorghum production in Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek using the AquaCrop model.

4.4.1 Performance of the CMIP5 Models

4.4.1.1 Comparison between Observed Rainfall and GCM Ensemble

Figure 8 compares observed rainfall for the past 20 years (1986/87-2004/05) in Thaba-Tseka Butha-Buthe, Leribe and Mohale's Hoek during the rainy season with the Ensemble (average simulated rainfall by CNRM-CM5, FGOALS-s2 and GFDL-ESM2M).

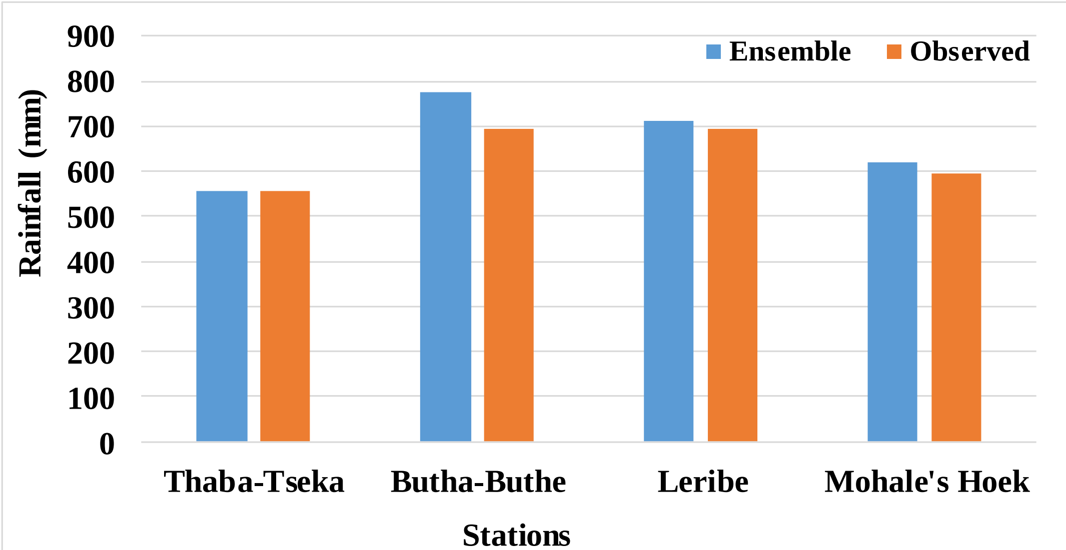
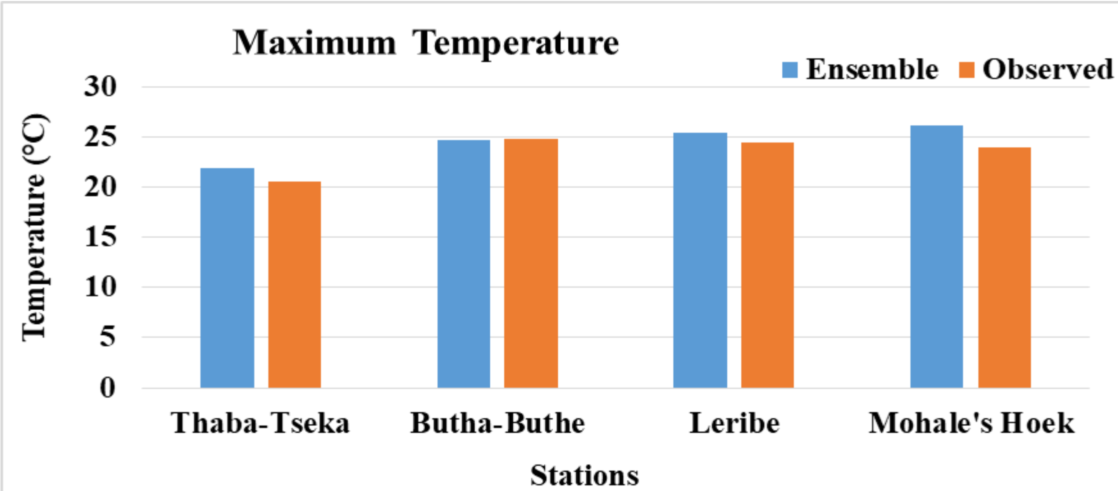


Figure 8: Comparison between observed and ensemble projected rainfall for Thaba-Tseka, Butha-Buthe, Leribe and Mohale’s Hoek from 1986/87-2004/05

The average of observed rainfall was 555 mm, 695 mm, 694 mm and 595 mm in Thaba-Tseka, Butha-Buthe, Leribe and Mohale’s Hoek respectively, against the ensemble averaged rainfall of 556 mm, 775 mm, 711 mm and 619 mm in Thaba-Tseka, Butha-Buthe, Leribe and Mohale’s Hoek correspondingly. The differences between the observed data and the ensemble simulated data were 1 mm, 80 mm, 17 mm and 24 mm in Thaba-Tseka, Butha-Buthe, Leribe and Mohale’s Hoek respectively.

4.4.1.2 Comparison between Observed Temperature and GCM Ensemble

Figure 9 presents a comparison for the baseline period (1986/87-2004/05) between the observed and ensemble simulated temperature by CNRM-CM5, FGOALS-s2 and GFDL-ESM2M in Thaba-Tseka, Butha-Buthe, Leribe and Mohale’s Hoek.



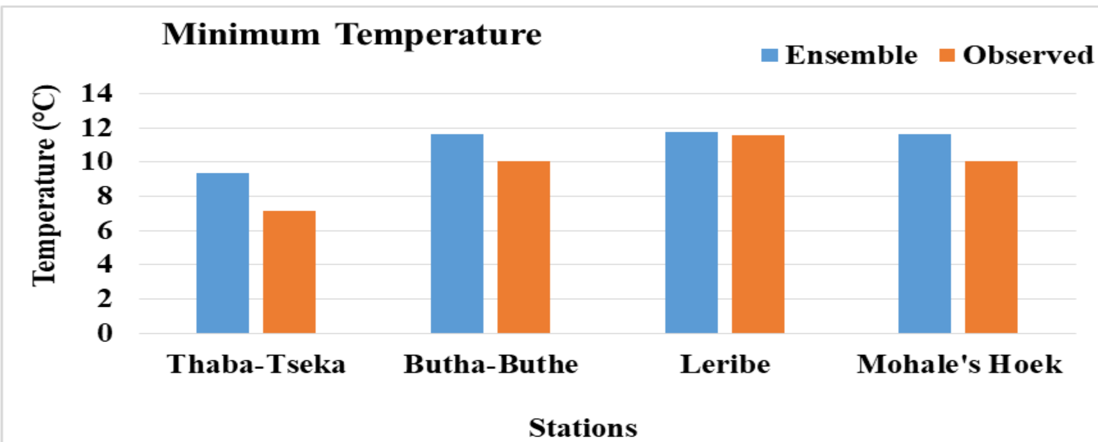


Figure 9: Comparison of observed and ensemble for maximum and minimum temperature in Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek from 1986/87-2004/05

The difference in maximum temperature between the ensemble and observed data is -0.1 ºC in Butha-Buthe and 2.2 °C, 1.1 ºC and 1.4 ºC in Mohale's Hoek, Leribe and Thaba-Tseka. For minimum temperature a greater difference was observed in Thaba-Tseka of 2.3 ºC, followed by Leribe and Butha-Buthe with 1.6 °C. A minor difference of 0.2°C was depicted in Mohale's Hoek district.

Table 11 shows the rank sum results for correlation coefficients and root mean square error values, the overall rank summation and the overall ranks for 11 GCM's for Leribe, Thaba-Tseka, Butha-Buthe and Mohale's Hoek.

Table 11: CMIP5 GCMs ranking based on Correlation Coefficient and Root mean square error for Leribe, Thaba-Tseka, Butha-Buthe and Mohale's Hoek

LERIBE	**r**	**RMSE**			**BUTHA-BUTHE**	**r**	**RMSE**		
GCM's	Rank Sum	Rank Sum	Overall Rank Sum	Overall Rank	GCM's	Rank Sum	Rank Sum	Overall Rank Sum	Overall Rank
MIROC/ESM	17	15	32	**4**	MIROC-ESM	24	23	47	9
CNRM/CM5	14	13	27	**3**	CNRM-CM5	13	11	24	**2**
CanESM2	26	27	53	11	CanESM2	26	25	51	10
FGOALS/s2	14	10	24	**1**	FGOALS-s2	13	14	27	**3**
BNU/ESM	24	18	42	9	BNU-ESM	19	20	39	5
MIROC5	14	23	37	6	MIROC5	27	26	53	11
GFDL/ESM2G	21	19	40	8	GFDL-ESM2G	19	19	38	**4**
MIROC/ESM/CHEM	23	19	42	10	MIROC-ESM-CHEM	22	22	44	7
GFDL/ESM2M	14	12	26	**2**	GFDL-ESM2M	10	13	23	**1**
MRI/CGCM3	18	20	38	7	MRI-CGCM3	22	23	45	8
BCC-CSM1-1	13	23	36	5	BCC-CSM1-1	20	21	41	6
THABA-TSEKA	**r**	**RMSE**			**MOHALE'S HOEK**	**r**	**RMSE**		
GCM's	Rank Sum	Rank Sum	Overall Rank Sum	Overall Rank	GCM's	Rank Sum	Rank Sum	Overall Rank Sum	Overall Rank
MIROC-ESM	16	17	33	**4**	MIROC-ESM	30	24	54	10
CNRM-CM5	15	16	32	**3**	CNRM-CM5	11	11	22	**2**
CanESM2	25	25	50	10	CanESM2	24	22	46	8
FGOALS-s2	10	13	23	**2**	FGOALS-s2	13	12	25	**3**
BNU-ESM	20	21	41	6	BNU-ESM	18	17	35	7
MIROC5	32	31	63	11	MIROC5	12	20	32	**4**
GFDL-ESM2G	23	23	46	8	GFDL-ESM2G	8	26	34	5
MIROC-ESM-CHEM	21	22	43	7	MIROC-ESM-CHEM	29	28	57	11
GFDL-ESM2M	10	12	22	**1**	GFDL-ESM2M	10	11	21	**1**
MRI-CGCM3	17	18	35	5	MRI-CGCM3	17	20	37	6
BCC-CSM1-1	23	25	48	9	BCC-CSM1-1	25	26	51	9

The models that gave rise to low rank values obtained from the summation of two metrics rank sum were CNRM-CM5, FGOALS-s2 and GFDL-ESM2M. The 3 out of the 11 CMIP5 models studied were therefore selected and used for examining the impact of future climate on sorghum yields in the study locations.

4.4.2 Climate Change Projections under RCP 4.5 Climate Scenario

This section presents a comparison between the observed data (1986/87-2004/05) and the GCMs including the Ensemble projected (2030/31-2059/60) rainfall, maximum and minimum temperatures.

4.4.2.1 Rainfall Projections

Table 12 presents the projected changes in rainfall based on CNRM-CM5, FGOALS-s2, GFDL-ESM2M models and the ensemble under RCP 4.5 climate scenario between the baseline climate data (1986/87 to 2004/05) and projected future climate (2030/31-2059/60) in Butha-Buthe, Thaba-Tseka, Leribe and Mohale’s Hoek.

Table 12: Projected Changes in Seasonal Rainfall between 1986/87- 2004/05 and 2030/31-2059/60 for Thaba-Tseka, Butha-Buthe, Leribe and Mohale’s Hoek

	Thaba-Tseka	Butha-Buthe	Leribe	Mohale's Hoek
Average of observed Rainfall (mm)	**555**	**695**	**694**	**595**
CNRM-CM5	145	686	657	611
% Change	-74	-1	-5	3
FGOALS-s2	158	718	663	640
% Change	-72	3	-4	8
GFDL-ESM2M	163	947	842	645
% Change	-71	36	21	8
Ensemble	155	783	721	632
% Change	-72	13	4	6

The FGOALS-s2, GFDL-ESM2M and the ensemble projected an increasing seasonal rainfall in Butha-Buthe corresponding to changes of 3 %, 36 %, and 13 % by FGOALS-s2, GFDL-ESM2M and the ensemble respectively. On the other hand, CNRM-CM5 projected a decline in rainfall (-1 %). In Leribe, CNRM-CM5 and FGOALS-s2 projected decreases in rainfall of -5 % and -4 % respectively, while GFDL-ESM2M and the ensemble projected increasing seasonal rainfall of 21% and 4 % respectively. All the models projected an increasing seasonal rainfall in Mohale's Hoek corresponding to changes of 3 %, 8 % and 6 % by CNRM-CM5, FGOALS-s2 and GFDL-ESM2M as well as the ensemble respectively. The CNRM-CM5 model projected an increase of 3 %, FGOALS-s2 and GFDL-ESM2M (8 %) and the ensemble (6 %). In Thaba-Tseka, all the models including the ensemble projected decreasing rainfall. In Thaba-Tseka, the change in rainfall ranged between -71 % to -74 %. This projected decline in rainfall over Lesotho has also been reported in other studies (Dejene *et al*., 2011; Gwimbi *et al.*, 2013; Malebajoa, 2010 and Zhou *et al.*, 2010).

4.4.2.2 Temperature Projections

Table 13 presents the projected changes in seasonal temperature based on CNRM-CM5, FGOALS-s2, GFDL-ESM2M models and the ensemble under RCP 4.5 climate scenario between observed (1986/87 to 2004/05) and future climate (2030/31 to 2059/60) in Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek.

Table 13: Projected Changes in Seasonal Temperature between 1986/87-2004/05 and 2030/31-2059/60 for Thaba-Tseka, Leribe, Mohale's Hoek and Butha-Buthe

Model	Climate Parameter	Thaba-Tseka	Leribe	Mohale's Hoek	Butha-Buthe
CNRM-CM5	Maximum Temperature (°C)	2.0	2.0	3.0	1.1
	Minimum Temperature (°C)	3.0	1.0	3.4	2.5
FGOALS-s2	Maximum Temperature (°C)	3.0	3.0	4.0	1.6
	Minimum Temperature (°C)	4.0	1.0	4.3	3.2
GFDL-ESM2M	Maximum Temperature (°C)	2.0	2.0	3.1	0.3
	Minimum Temperature (°C)	3.0	1.0	3.5	2.7
Ensemble	Maximum Temperature (°C)	2.0	3.0	3.3	0.9
	Minimum Temperature (°C)	4.0	1.0	3.7	2.8

All the models including the ensemble projected an increase in both maximum and minimum temperatures in all the areas studied. The change in Thaba-Tseka for maximum temperature ranged between 2 to 3 ºC, and 3 to 4 ºC for minimum temperature. At Mohale's Hoek the change in maximum temperature ranged between 3 ºC and 4 ºC, whereas minimum temperature increase of 3.1 to 4.3 °C is projected. The projected increase for maximum temperature in Leribe ranged between 2 and 3 ºC, while an increase by 1 °C for minimum temperature is anticipated in the future. GFDL-ESM2M showed the lowest projected increase in maximum temperature of 0.3 ºC, while FGOALS-s2 showed the highest increase of 1.6 °C in Butha-Buthe. The CNRM-CM5 and the ensemble projected increases of 1.1 ºC and 0.9 ºC respectively. Minimum temperature is projected to increase by 2.5 °C to 3.2 °C.

Overall, all the CIMP5 models used in this study predicted increasing maximum and minimum temperatures under RCP 4.5 scenario for all the four districts studied. These findings are in agreement with those of Malebajoa (2010) and Lesotho Meteorological Services (2000) that indicated that Lesotho will experience increased temperature in the future. Dejene *et al*. (2011) also reported that during the 2046-2065 time period, an increase in temperature by 2.0 ºC to 2.5 ºC is anticipated over Lesotho. Other studies conducted in Lesotho also revealed that temperature will be warming over Lesotho (Gwimbi *et al*., 2013; Zhou *et al*., 2010).

4.4.3 Sorghum Yield Projections

This section presents the results on sorghum yield projections obtained from the AquaCrop model using the projected rainfall and temperature obtained from the 3 suitable CIMP 5 models.

4.4.3.1 Comparison between the Observed and Simulated Sorghum Yields under Current Climate

Table 14 presents a comparison between the observed sorghum yields and the simulated sorghum yields by the AquaCrop model for the four study districts.

Table 14: Comparison between AquaCrop Simulated and Observed Sorghum yields for 1999/2000 to 2017/2018 cropping seasons in Leribe, Thaba-Tseka, Mohale's Hoek and Butha-Buthe

	Leribe		**Butha-Buthe**		**Thaba-Tseka**		**Mohale's Hoek**	
Cropping Season	Observed Sorghum Yield (Kg/ha)	Simulated Sorghum Yield (Kg/ha)	Observed Sorghum Yield (Kg/ha)	Simulated Sorghum Yield (kg/ha)	Observed Sorghum Yield (Kg/ha)	Simulated Sorghum Yield (Kg/ha)	Observed Sorghum Yield (Kg/ha)	Simulated Sorghum Yield (Kg/ha)
1999/2000	4160	4440	1080	2650	700	930	470	2750
2000/2001	1060	2760	610	2450	610	1170	1020	2550
2001/2002	520	2640	330	2510	390	1470	250	2650
2002/2003	710	2730	410	2350	1050	1310	740	2900
2003/2004	430	2640	1000	2810	910	1290	350	2400
2004/2005	540	2820	430	2640	1200	1520	660	2780
2005/2006	590	2830	520	2550	3040	2400	330	2640
2006/2007	450	2750	160	2460	280	1330	170	2220
2007/2008	580	2950	130	2340	290	740	170	2620
2008/2009	580	2800	660	2860	710	930	630	2750
2009/2010	780	2950	930	2760	810	1320	690	2750
2010/2011	550	2760	310	2440	880	860	440	2940
2011/2012	420	2900	640	2760	530	1180	620	2600
2012/2013	470	2880	900	2870	700	1370	830	2980
2013/2014	550	2210	490	2680	370	760	460	2830
2014/2015	990	2480	370	2700	150	790	720	3090
2015/2016	90	2800	280	1670	100	1270	330	1990
2016/2017	1010	3000	440	1510	560	1040	850	2700
2017/2018	750	590	540	2540	310	1300	730	2470
Average	801	2732	538	2502	716	1209	550	2264

As seen in this table, the AquaCrop model simulated higher sorghum yields than those of observed in all the four districts. The predicted sorghum yields ranged between 1510 kg/ha and 2870 kg/ha at Butha-Buthe. At Leribe, Mohale's Hoek, and Thaba-Tseka sorghum yields ranged from 590 kg/ha to 4440 kg/ha, 1990 kg/ha to 3090 kg/ha, and 740 kg/ha to 2400 kg/ha respectively. The observed sorghum yield ranged between 130 kg/ha to 1080 kg/ha, 90 kg/ha to 4160, 17 kg/ha to 1020 kg/ha and 10 kg/ha to 3040 kg/ha at Butha-Buthe, Leribe, Mohale's Hoek and Thaba-Tseka respectively. The AquaCrop model simulated lower sorghum yields in Leribe compared to observed sorghum yield for 2017/2018 cropping season in which the observed sorghum yield was 750 kg/ha against the simulated yield of 590 kg/ha. The model also predicted lower yields for Thaba-Tseka for 2005/2006 compared to the observed yield, in which the simulated yield was 2400 kg/ha against the observed yield of 3040 kg/ha.

The average simulated sorghum yields were 1209 kilograms per hectare, 2502 kilograms per hectare, 2732 kilograms per hectare, 2664 kilograms per hectare and in Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek respectively against the average observed yields of 716 kilograms per hectare, 538 kilograms per hectare, 801 kilograms per hectare and 580 kilograms per hectare in Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek respectively.

Table 15 presents the correlation coefficients between the observed sorghum yields and the simulated yields in Thaba-Tseka, Leribe, Mohale's Hoek and Butha-Buthe.

Table 15: Correlation Coefficient between Observed and Simulated Sorghum Yield in Thaba-Tseka, Leribe, Mohale's Hoek and Butha-Buthe

Station	**Correlation Coefficient (r)**	**P- value**
Thaba-Tseka	0.77	0.00
Leribe	0.56	0.01
Mohale's Hoek	0.43	0.07
Butha-Buthe	0.50	0.03

These results depict positive correlation coefficients between observed and simulated sorghum yields. The correlation coefficients are statistically significant in Thaba-Tseka (r=0.77) and p-value is 0.03, in Leribe (r=0.56) and Butha-Buthe (r=0.50). The correlation coefficient between observed and simulated sorghum yield is 0.43 in Mohale's Hoek with ($p>0.05$). The correlation coefficient is not statistically significant at 5% significance level.

4.4.3.2 Projected Sorghum Yields under RCP 4.5 Climate Scenario

Table 16 presents the projected sorghum yields based on the projected rainfall and temperature data by the 3 suitable GCMs, namely, CNRM-CM5, FGOALS-s2, GFDL-ESM2M and the ensemble in Thaba-Tseka, Leribe, Mohale's Hoek and Butha-Buthe for the period 2030/2031 to 2058/2059.

Table 16: Change in projected sorghum yield between 1986/87- 2017/18 and 2030/31-2059/60 for Thaba-Tseka, Leribe, Mohale's Hoek and Butha-Buthe

	Thaba-Tseka	Butha-Buthe	Leribe	Mohale's Hoek
Average of Observed Yield (Kg/ha)	**812**	**642**	**1236**	**581**
CNRM-CM5	1093	826	941	871
Change	281	185	-295	290
% Change	35	29	-24	50
FGOALS-s2	932	1494	1162	839
Change	120	852	-73	258
% Change	15	133	-6	44
GFDL-ESM2M	857	3995	2838	3174
Change	44	3354	1603	2593
% Change	5	523	130	446
Ensemble	388	1254	2952	293
Change	-424	612	1716	-287
% Change	-52	95	139	-49

The GFDL-ESM2M model projected the highest yields compared to the average observed yields in Mohale's Hoek, Leribe and Butha-Buthe. In Thaba-Tseka, the projected percentage change in sorghum yield by CNRM-CM5 was 35 % while FGOALS-s2 and GFDL-ESM2M projected percentage changes of 15 % and 5 % respectively. The CNRM-CM5 projected percentage changes in sorghum yields of 50 %, 29 % and -24 % in Mohale's Hoek, Butha-Buthe and Leribe respectively.

The ensemble model projected sorghum yield declines in Thaba-Tseka (-52 %) and Mohale's Hoek (-49 %), this decrease could be attributed to the projected decline in rainfall during the 2030/31 to 2059/60 cropping season. Sorghum yield is projected to increase in Leribe (139 %) and Butha-Buthe (95 %). An increase in sorghum yield could be explained by the projected increases in temperature and rainfall. Increased rainfall in these regions will increase the availability of soil moisture during the cropping season hence accelerate sorghum growth and development towards physiological maturity. The ensemble results showed that rainfall will increase by 13 % in Butha-Butha whereas an increase of 4 % is projected in Leribe.

In Mohale's Hoek district, one of the dry areas in Lesotho the ensemble projected temperature increase at the rate of 3.3 ºC for maximum and 3.7 ºC for minimum temperature during the growing season which could be a threat to sorghum production. Although rainfall is anticipated to increase by 6 %, high rate of evapotranspiration due to the projected high temperature could adversely affect sorghum productivity in this region.

These findings are in agreement with those from various similar studies done in different locations. (Bosire, 2019; Gwimbi *et al.*, 2012; Lesotho Meteorological Services, 2000; Msongaleli *et al*., 2014 and Zhou *et al*., 2010) that showed that sorghum yields could increase in various geographical locations under changing climate.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter gives major conclusions drawn from this study and the recommendations appropriate to sorghum farmers of Thaba-Tseka, Butha-Buthe, Leribe and Mohale's Hoek and farmers in other comparable biophysical environments in Lesotho, as well as to researchers and policy makers.

5.2 Conclusions

Rainfall across the study areas in Lesotho is reliable and characterized with uniform to moderate distribution and was the major determinant of sorghum productivity in all the four study districts. This together with the stable temperature during the planting season makes the study districts suitable for sorghum production. Though insignificant, the increasing seasonal rainfall trends, significant increasing trends in minimum and maximum temperature presents high prospects for sorghum production in Lesotho. Consequently, Lesotho is likely to experience increased number of frost free days and increased heat units that are supportive of improved sorghum development and growth and eventual productivity, food security, and income of farmers who depend mainly on agriculture for their living.

Seasonal rainfall in the majority of the study locations, except for Thaba-Tseka will increase in the future (2030/31 to 2059/60) based on the ensemble. However, CNRM-CM5, FGOALS-s2 and GFDL-ESM2M present uncertainty in projected rainfall across the regions studied. All the climate models including the ensemble projected an increasing temperature in the future in all the locations studied. Under RCP 4.5, sorghum yields are projected to increase in the future based on the ensemble in Leribe and Butha-Buthe whereas a decline is projected at Mohale's Hoek and Thaba-Tseka during the cropping period 2030/31 to 2059/60.

5.3 Recommendations

In this section recommendations based on the finding obtained in this study are provided to policy makers, researchers and farmers.

5.3.1 Recommendations to Policy Makers

The government of Lesotho should promote agricultural policies and strategies that promote sorghum production at large scale while integrating climate smart technologies and practices, soil and water management.

5.3.2 Recommendations to Farmers

Sorghum farmers should increase area under sorghum production to take advantage of the projected increase in rainfall, temperature, heat units and frost free days to increase and sustain productivity and food security.

5.3.3 Recommendations to Researchers

The research community should conduct further investigations to establish the impact of climate variability and change on sorghum production, taking into account, climatic derivatives such as growing degree days, evapotranspiration, and management factors.

REFERENCES

Ahmed, K., Sachindra, D. A., Shahid, S., Demirel, M. C., and Chung, E.-S. (2019). Selection of multi-model ensemble of GCMs for the simulation of precipitation based on spatial assessment metrics. *Hydrology and Earth System Science.* https://doi.org/10.5194/hess-2018-585 Link valid on 9th December 2020

Alemayehu, A., and Bewket, W. (2016). Local climate variability and crop production in the central highlands of Ethiopia. *Environmental Development*, **19,** 36–48

Bewick, V., Cheek, L., and Ball, J. (2003). Statistics Review Correlation and Regression. *Critical Care*, *7*(6), 451. https://doi.org/10.1186/cc2401 Link valid on 12th August 2020

Bewket, W. (2009). Rainfall variability and crop production in Ethiopia: Case study in the Amhara region. *In Proceedings of the 16th International Conference of Ethiopian Studies.Trondheim.*, Vol. 3, pp.**14**, 823–836,

Bosire, E., Gitau, W., Karanja, F., and Ouma, G. (2019). Analysis of Climate Variability, Trends and expected implication on crop production in a Semi-Arid Environment of Machakos County, Kenya. *Advances in Agriculture Sciences,* **1**, 99-115.

Bosire, E., Karanja, F., Ouma, G., and Gitau, W. (2018). Assessment of Climate Change Impact on Sorghum Production in Machakos County. *Sustainable Food Production*, **3**, 25–45. https://doi.org/10.18052/www.scipress.com/SFP.3.25

Botai, C., Botai, J. O., and Adeola, A. (2018). Spatial distribution of temporal precipitation contrasts in South Africa. *South African Journal of Science*, **114**, (7/8). https://doi.org/10.17159/sajs.2018/20170391

Bureau of Statistics (2017). Statistical Report 2016/17 Agricultural Production Survey Crops. No.33 of 2017. Maseru, Lesotho. www.bos.gov.ls.

Chai, T., and Draxler, R. R. (2014). Root mean square error (RMSE) or mean absolute error (MAE)? *Geoscientific Model Development Discussions*, **7** (1), 1525–1534. https://doi.org/10.5194/gmdd-7-1525-2014

de Luis, M., González-Hidalgo, J. C., Brunetti, M., and Longares, L. A. (2011). Precipitation concentration changes in Spain 1946–2005. *Natural Hazards and Earth System Sciences*, **11**(5), 1259–1265. https://doi.org/10.5194/nhess-11-1259-2011

Dejene, A., Midgley, S., Marake, M. V., and Ramasamy, S. (2011). Strengthening Capacity for Climate Change Adaptation in Agriculture: Experience and Lessons from Lesotho. Maseru, Lesotho

Department of Agriculture, Forestry and Fisheries. (2010). *Sorghum Production Guideline*. Department of Agriculture, Forestry and Fisheries. South Africa https://1pdf.net/sorghum-department-of-agriculture-forestry-and fisheries_58f2c923f6065d3876eb2844 Link valid on 27 February 2020

Ezenwaji, E., Nzoiwu, C., and Chima, G. (2017). Analysis of Precipitation Concentration Index (PCI) for Awka Urban Area, Nigeria. *Hydrology: Current Research*, *08*. https://doi.org/10.4172/2157-7587.1000287

FAO. (2012). FAO in Lesotho Country Brief. Food and Agriculture Organization of the United Nations, Rome. http://www.ipcinfo.org/fileadmin/user_upload/en/NOBILE-1012-4/Country%20Brief%20Lesotho%20Sept%202012.pdf Link valid on 17th May 2020

FAO/WFP. (2005). *Special Report FAO/WFP Crop and Food Supply Assessment Mission to Lesotho*. Food and Agriculture Organization of the United Nations, World Food Programme, Rome. http://www.fao.org/giews/ Link valid on 14th August 2020

Ghaedi, S., and Shojaian, A. (2020). Spatial and temporal variability of precipitation concentration in Iran. *Geographica Pannonica*, **24**, (4), Article 4. https://doi.org/10.5937/gp24-27361

Gommes, R., Challinor, A., Das, H., Dawod, M. A., Mariani, L., Tychon, B., Krüger, R., Otte, U., Vega, R. E. R., and Trampf, W. (2010). Guide to Agricultural Meteorological Practices. *World Meteorological Organization*, *134*.

Grossi, M. C., Justino, F., Rodrigues, R. de Á., and Andrade, C. L. T. (2015). Sensitivity of the sorghum yield to individual changes in climate parameters: Modelling based approach. *Bragantia*, **74**(3), 341–349.

Gwimbi, P., Thomas, T. S., and Hachigonta, S. (2013). Assessing the vulnerability of agriculture to climate change in Lesotho. *Southern African Agriculture and Climate Change: A Comprehensive Analysis. International Food Policy Research Institute, Washington, DC Http://Dx. Doi. Org/10.2499/9780896292086*.

Gwimbi, P., Hachigonta, S., Majela, L., and Sibanda, D. (2012). Southern African Agriculture and Climate Change: A Comprehensive Analysis-Lesotho. *IFRI, FANRPAN, CGIAR, Research Program on Climate Change, Agriculture and Food Security, CCAFS*. https://www.preventionweb.net/go/34629

Hare, F. K. (1983). *Climate and desertification: A revised analysis* (Vol. 44). World Meteorological Organization.

Hudo, N. (2016). Assessing the Impact of Climate Variability and Change on Sorghum Yield over Gadaref Area in Sudan [MSc Thesis] University of Nairobi, Kenya. http://erepository.uonbi.ac.ke/handle/11295/97907

Ibrahim, A. M. (2015). The Impact of Rainfall on the Yields of Staple Crops-Sorghum and Sesame in Sudan. *Journal of Plant Science & Research*, **2,** (2), 1–4.

Kamworapan, S., and Surussavadee, C. (2019). Evaluation of CMIP5 Global Climate Models for Simulating Climatological Temperature and Precipitation for Southeast Asia. *Advances in Meteorology*, *2019*, 1–18. https://doi.org/10.1155/2019/1067365

Kandji, S. T., Verchot, L., and Mackensen, J. (2006). Climate change and variability in the Sahel region: Impacts and adaptation strategies in the agricultural sector. World Agroforestry Centre Nairobi, Kenya.

Kuri, S. K., Hossain, M. J., and Saha, M. (2014). Trend Analysis of Climate Variables (air Temperature and Rainfall) and Its Influences on Rice Yield: A Case Study from Mymensingh District of Bangladesh. 8.

Laidlaw, H. K. C., and Godwin, I. D. (2008). Sorghum. In C. Kole & T. C. Hall (Eds.), *Compendium of Transgenic Crop Plants* (pp. 157–176). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781405181099.k0106

Lesotho Meteorological Services. (2000). National Report on Climate Change. Ministry of Natural Resources, Maseru, Lesotho.

Lesotho Meteorological Services. (2007). Lesotho's National Adaptation Programme of Action (NAPA) on Climate Change. Ministry Of Natural Resources Lesotho, Meteorological Services, Maseru, Lesotho

Lesotho Meteorological Services. (2013). Lesotho's Second National Communication under the United Nations Framework Convention on Climate Change. Ministry of Energy, Meteorology and Water Affairs Maseru, Lesotho.

Lesotho Meteorological Services. (2017). Lesotho's National Climate Change Policy. Ministry of Energy and Meteorology, Maseru, Lesotho.

Magalhães, I. D., Lyra, G. B., Souza, J. L. de, Teodoro, I., Rocha, A. E. Q. da, Júnior, C. A. C., Lyra, G. B., Junior, R. A. F., Carvalho, A. L. de, and Ferraz, R. L. de S. (2019). Performance of the Aquacrop model for bean (Phaseolus vulgaris L.) under irrigation condition. *Australian Journal of Crop Science*, 1188–1196.

Maher, P., Vallis, G. K., Sherwood, S. C., Webb, M. J., and Sansom, P. G. (2018). The Impact of Parameterized Convection on Climatological Precipitation in Atmospheric Global

Climate Models. *Geophysical Research Letters*, **45**(8), 3728–3736. https://doi.org/10.1002/2017GL076826

Malebajoa, M. (2010). Climate change impacts on crop yields and adaptive measures for agricultural sector in the lowlands of Lesotho. [MSc Thesis]. *Lunds Universitets Naturgeografiska Institution-Seminarieuppsatser*.

Maro, P. (2011). Environmental change in Lesotho: An analysis of the causes and consequences of land-use change in the lowland region. *Springer Verlag.*

Matarira, C. H., Pullanikkatil, D., Kaseke, T., Shava, E., and Manatsa, D. (2013). Socio-economic impacts of climate change on subsistence communities. *International Journal of Climate Change Strategies and Management*, **5**(4).

Matela, L., (2012). Economic Review; Lesotho's 2011/2012 Crop Forecasting. Maseru, Lesotho www.centralbank.org.ls/publications Link valid on 22nd January 2020

Mavi, H. S., and Tupper, G. J. (2004). Agrometeorology: Principles and Applications of Climate Studies in Agriculture. *CRC Press.*

Mekbib, S. B., Olaleye, A. O., Mokhothu, M. N., Johane, M., Tlali, S. B., and Godeto, T. W. (2011). Assessment on the Adaptive Capacity of the Machobane Farming System to Climate Change in Lesotho. *Publisher: African Technology Policy Studies Network (ATPS).*

Mibulo, T., and Kiggundu, N. (2018). Evaluation of FAO AquaCrop Model for Simulating Rainfed Maize Growth and Yields in Uganda. *Agronomy*, **8**(11), 238. https://doi.org/10.3390/agronomy8110238

Mock, N. (2005). Vulnerability assessment methodology review, Lesotho country report. *Southern African Development Community: Food, Agriculture and Natural Resources, Regional Vulnerability Assessment Committee (SADC-FANR RVAC) Gabarone, Botswana*.

Moeletsi, M. E. (2004). Agroclimatic characterization of Lesotho for dryland maize production [MSc Thesis]. Department of Soil, Crop and Climate, University of the Free State, Bloemfontein, South Africa.

Moeletsi, M. E., and Walker, S. (2013). Agroclimatological suitability mapping for dryland maize production in Lesotho. *Theoretical and Applied Climatology*, **114**(1–2), 227–236.

Mosenene, L. (1999). Soil-water and conservation tillage practices in Lesotho: Experiences of SWACAP. *P G.* Kaumbutho., & TE Simalenga (Eds), Conservation Tillage with Animal Traction. A Resource Book of the Animal Traction Network for Eastern and Southern Africa (ATNESA). Harare. Zimbabwe. 173. http://www.atnesa.org Link valid on 22nd January 2020

Moshoeshoe-Chadzingwa, M. M. (2007). Assessment of Agricultural information needs in African, Caribbean and Pacific (ACP) States: Country Study: Lesotho. 2. CTA, Wageningen, the Netherlands https://hdl.handle.net/10568/52383 Link valid on 21st January 2021

Mphale, M. M. (2003). HIV/AIDS and Food insecurity in Lesotho; In Draft, London, Forum for Food Security in Southern Africa. Maseru, Lesotho. https://reliefweb.int/sites/reliefweb.int/files/resources/1FE90B3320D27BF3C1256D5000567FB6-odi-les-25jun.pdf Link valid on 18th August 2020

Mphale, M. M., Rwambali, E. G., and Sechaba Consultants. (2003). Lesotho Food Security Issues Paper For Forum for Food Security in Southern Africa. https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/5615.pdf Link valid on 9th July 2020

Msongaleli, B., Rwehumbiza, F., Tumbo, S. D., and Kihupi, N. I. (2014). Sorghum yield response to changing climatic conditions in semi-arid central Tanzania: Evaluating crop simulation model applicability. *Journal of Agricultural Sciences*, **5**, 822–833.

Nhemachena, C., Greenwell M., and Sibusiso N. (2017). Agricultural growth trends and outlook for Lesotho. ReSAKSS-SA Annual Trends and Outlook Report 2016. https://doi.org/10.13140/RG.2.2.33580.56961 Link valid on 12th July 2020

Nhlapo, L. A. (2017). Temperature variability and change at various altitudes across Lesotho and adjoining areas: Implications for agriculture [MSc Thesis]. University of Witwatersrand. Johannesburg. South Africa.

Oliver, J. E. (1980). Monthly Precipitation Distribution: A Comparative Index. *The Professional Geographer*, **32**(3), 300–309. https://doi.org/10.1111/j.0033-0124.1980.00300.

Pohlert. (2015). Non-Parametric Trend Tests and Change-Point Detection, R package version *0.0.1*.ResearchGate. https://www.researchgate.net/publication/274014742_trend_Non-Parametric_Trend_Tests_and_Change-Point_Detection_R_package_version_001 Link valid on 19th July 2020

Prasad, P. V. V., Staggenborg, S. A., and Ristic, Z. (2008). Impacts of drought and/or heat stress on physiological, developmental, growth, and yield processes of crop plants. *Response of Crops to Limited Water: Understanding and Modeling Water Stress Effects on Plant Growth Processes*, **1**, 301–355.

Raes, D. (2017). *AquaCrop training handbook I. Understanding AquaCrop*. Food and Agriculture Organization, Rome.

Raes, Dirk, Steduto, P., Hsiao, T. C., and Fereres, E. (2009). AquaCrop—the FAO crop model to simulate yield response to water: II. Main algorithms and software description. *Agronomy Journal*, **101**(3), 438–447.

Ramirez-Villegas, J., and Jarvis, A. (2010). *Downscaling Global Circulation Model Outputs: The Delta Method Decision and Policy Analysis Working Paper No. 1*. http://www.ccafs-climate.org/downloads/docs/Downscaling-WP-01.pdf Link valid on 16th February 2020

Schmitz, G., and Rooyani, F. (1987). Lesotho Geology, Geomorphology, Soils. *National University of Lesotho*, 209, Roma, Maseru.

Sekoli, M. S., and Morojele, M. E. (2016). Sorghum-Productivity-Trends-and-Growth-Rate-for-Lesotho1.pdf. *Global Journal of Agricultural Research*, *4*(1), 52–57. http://www.eajournals.org/wp-content/uploads/Sorghum-Productivity-Trends-and-Growth-Rate-for-Lesotho1.pdf

Shah, S. A. A., Nisa, S., Khan, A., and Rahman, Z. U. (2012). Trends and variability in climate parameters of Peshawar district. *Science Technology and Development*, **31**(4), 341–347.

Silici, L. (2010). Conservation agriculture and sustainable crop intensification in Lesotho. Food and Agriculture Organization of the United Nations, Rome.

Silva, V. de P. R. da, Silva, R. A. e, Maciel, G. F., Braga, C. C., Silva Júnior, J. L. C. da, Souza, E. P. de, Almeida, R. S. R., Silva, M. T., and Holanda, R. M. de. (2017). Calibration and validation of the AquaCrop model for the soybean crop grown under different levels of irrigation in the Motopiba region, Brazil. *Ciência Rural*, **48**(1). https://doi.org/10.1590/0103-8478cr20161118

Steduto, P., Hsiao, T. C., Raes, D., and Fereres, E. (2009). AquaCrop—The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agronomy Journal*, **101**(3), 426–437.

Todorovic, M., Albrizio, R., Zivotic, L., Saab, M.-T. A., Stöckle, C., and Steduto, P. (2009). Assessment of AquaCrop, CropSyst, and WOFOST models in the simulation of sunflower growth under different water regimes. *Agronomy Journal*, **101**(3), 509–521.

Tongwane, M. I., and Moeletsi, M. E. (2015). Intra-seasonal rainfall variability during the maize growing season in the northern lowlands of Lesotho. *Theoretical and Applied Climatology*, **120**(3–4), 575–585.

Valli, M., Sree, K. S., and Krishna, I. V. M. (2013). *Analysis of Precipitation Concentration Index and Rainfall Prediction in various Agro-Climatic Zones of Andhra Pradesh, India*. **2**, 9.

Vanderlip, R.L, (1993). How a sorghum plant develops. Cooperative Extension Service Contribution, NO.1203 Kansas Agricultural Experiment Station Manhattan, Kansas. https://scholar.google.com/scholar_lookup?title=How+a+sorghum+plant+develops&author=Vanderlip%2C+R.+L.&publication_year=1993 Link valid on 12th May 2020

Wagesho, N., Goel, N. K., and Jain, M. K. (2013). Temporal and spatial variability of annual and seasonal rainfall over Ethiopia. *Hydrological Sciences Journal*, **58**(2), 354–373. https://doi.org/10.1080/02626667.2012.754543

WFP. (2006). Assessment of 2005/06 Agricultural Production in Lesotho. Maseru, Lesotho. https://documents.wfp.org/stellent/groups/public/documents/ena/wfp109465.pdf Link valid on 25th May 2020

WMO. (2010). Guide to Agricultural Meteorological Practices. World Meteorological Organization. http://www.wamis.org/agm/gamp/GAMP_Chap10.pdf Link valid on 12th May 2020

Yadav, R., Tripathi, S. K., Pranuthi, G., and Dubey, S. K. (2014). Trend analysis by Mann-Kendall test for precipitation and temperature for thirteen districts of Uttarakhand. **16**(2), 9.

Yohannes, H. (2015). A Review on Relationship between Climate Change and Agriculture. *Journal of Earth Science & Climatic Change*, **07**(02). https://doi.org/10.4172/2157-7617.1000335

Zewdu, E., Hadgu, G., and Gebreyes, L. (2020). Impacts of climate change on sorghum production in North Eastern Ethiopia. *African Journal of Environmental Science and Technology*, **14**, 49–63. https://doi.org/10.5897/AJEST2019.2803

Zhou, P., Gwimbi, P., Maure, G. A., Johnston, P., Kanyanga, J. K., Mugabe, F. T., Manyats, A. M., Masarirambi, M. T., Thomas, T. S., and Sepo, H. A. (2010). Assessing the vulnerability of agriculture to climate change in southern Africa. Synthesis Report. *Food, Agriculture and Natural Resources Policy Analysis Network (FANRPAN). Pretoria, South Africa*.