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CLIMATE CHANGE IMPACTS ON CROP YIELDS AND ADAPTIVE MEASURES FOR AGRICULTURAL SECTOR IN THE LOWLANDS OF LESOTHO.

Cereal crops (by Ministry of Agriculture, 2000)

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CLIMATE CHANGE IMPACTS ON CROP YIELDS AND ADAPTIVE MEASURES FOR AGRICULTURAL SECTOR IN THE LOWLANDS OF LESOTHO

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Abstract

Climate change has emerged as the most prominent of the global environment issues and there is a need to evaluate its impact on the agriculture. General Circulation Models (GCMs) which are considered as the most advance tools for estimating future climate change scenarios operate on coarse resolutions. It is for this reason the climate change model MAGICC coupled to SCENGEN developed by the IPCC was used for climate change simulations, since it has an advantage of having spatially adjusted GCMs. This study was conducted in Lowlands of Lesotho, which is situated in the western part of Lesotho.

In order to estimate the level of climate change impact on the three main cereal crops in terms of cropped area and production (sorghum, wheat, and maize), climate change scenarios of precipitation and temperature were developed for lowlands of Lesotho. Baseline climate was based on the 29 years-period, 1980-2008 of the mean monthly normal. The two time slices 2030-2050 and 2080-2100 (near-term and long-term) were chosen. The choice of these time slices was justified by the availability of demographic projections for the areas at those periods. The A2 (medium-high GHG emission pathway) and B2 (medium-low) were used to produce future scenarios of the study area. The changes of climate variables were applied to crop simulation model called CROPWAT to simulate future crop yields. The model was first calibrated. It was run without taking into account CO_2 fertilization effect.

When the two stated emission scenarios were incorporated in the analysis, the comparison between future scenarios and reference period highlighted higher monthly averages of maximum temperatures with differences higher than 4-5.8 °C for B2 and A2 at the year 2100. Results also showed that depending on the level of future emissions, the average seasonal temperature increase in the study area by the end of the twenty-first century will be higher in winter and spring between 3 and 5.8 °C. The MAGICC/SCENGEN outputs also in 2100 predicted significant reductions of the amount of rainfall -27% and - 47% under B2 and A2, respectively, particularly in spring and summer. Under A2 and B2 most GCMs predicted winter and autumn precipitation increase. Crop modeling result suggested that under climate change the yield per hectare for the three crops would fall consistently as temperature rises beyond 2.5°C and rainfall decrease. The decrease is higher for rainfed maize, as compared to sorghum and wheat since they have mechanisms to withstand drought conditions during crop maturity stage.

These findings have important implications for Lesotho's agricultural policy and country strategies for adapting to climate variability and change. There are several potential adaptation strategies that may be used to offset the negative impacts of climate change on crop yields. These include switching to drought-tolerant small grains and cereal varieties, and appropriate management practices. Small farmers should be helped to combine into big farming units to increase irrigation efficiency. More research on climate change impacts on crop yields is called for to generate technologies that equip farmers to adapt to the effects of climate change.

Keywords: Climate change, A2 and B2 SRES, MAGICC/SCENGEN, CROPWAT, Crop Yields, adaptive measures

Summary

Climate change has emerged as the most outstanding of the environmental challenges and there is a necessity to evaluate its impacts on the vulnerable development sectors such as agriculture. In this study, spatially adjusted general circulation models and crop models were used to simulate climate change scenarios and the associated cereal crops yields for the western lowlands of Lesotho for the year 2030-2050 and 2080-2100. Focus was placed on three main cereal crops namely sorghum, wheat and maize. The models predicted an increase in monthly mean temperature and a decline in monthly rainfall for the area. With these variations on temperature and rainfall, the study indicated that the yield per hector for the three cereals would decline considerably. These findings suggest that Lesotho should initiate adaptive measures, such as switching to drought resistant crops, in order to offset the negative impacts of climate change on crop yields. The government is advised to organise small farming groups into larger farming communities and to strife for efficient irrigation. Research geared towards the development of technologies that may equip farmers to adapt to climate change effects is recommended for the country.

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LIST OF ACRONYMS

AAC	Africa Agriculture Climate
AOGCM	Atmosphere-Ocean General circulation Model
AR4	Fourth Assessment Report
BBC	British Broadcasting Co-operation
BOS	Bureau Of Statistics
CCCMA	Canadian Centre for Climate Modeling & Analysis
CO_2	Carbon dioxide
CROPWAT	Crop-Water Model
CWR	Crop Water Requirements
Dr	Depletion from the root-zone
ENSO	El Niño-Southern Oscillation
ETa	Actual crop evapotranspiration
ETo	Reference Evapotranspiration
ETc	Crop evapotranspiration
FAO	Food and Agriculture Organization, UN
GCM	General Circulation Model
GISS-EH	Goddard Institute for Space Studies
GHG	Green House Gas
GFDL	Geophysical Fluid Dynamics Laboratory
Ha	Hectare
ICRISAT	International Crop Research Institute for Semi-Arid Tropics
IPCC	Intergovernmental Panel on Climate Change
IITA	International Institute of Tropical Africa
IRIN	Integrated Regional Information Networks
ITCZ	Intertropical Convergence Zone
Kc	Crop coefficient
*K*y	Yield reduction factor
Ks	Water stress coefficient
Lat	Latitude
LMS	Lesotho Meteorological Services
Lon	Longitude
LVAC	Lesotho Vulnerability Assessment Committee
MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change
mt	metric tonnes
NGO	Non-Governmental Organisation
OTA	Office of Technology Assessment
P_{tot}	Total rainfall
PE	Effective rainfall
RAW	Readily Available Water
RMSE	Root Mean Square Error
SADC	Southern African Development Community
SCENGEN	SCEnarioGENerator
SRES	Special Report on Emissions Scenarios
STDV	Standard deviation
TAR	Third Assessment Report

TAW	Total Available Water
T_{max}	Maximum Temperature
T_{min}	Minimum Temperature
UKHADCM3	United Kingdom Hadley Centre for Climate Prediction
UNFCCC	United Nations Framework Convention on Climate Change
USDA	United States Department of Agriculture
USA	United States of America
WFP	World Food Programme
WG11	Working Group two
WPP	World Population Prospects
Ya	Actual yield, mt ha^{-}1
Ym	Maximum yield, mt ha^{-}1

1: INTRODUCTION

The possible implications for crop yields of climate change [1] have prompted concern worldwide (Fischer et al., 2005). In the coming decades, global agriculture faces the prospect of a changing climate (McCarthy et al., 2007), as well as the known challenge of continuing to feed the world's population, projected to be 9.2 billion by about the year 2050 (Lutz et al., 2001). Since the TAR, progress in understanding how climate is changing in space and in time has been gained through better understanding of uncertainties, and a wider variety of measurements (Boko et al., 2007). Global mean surface temperatures have risen by 0.74°C ± 0.18°C when estimated by a linear trend over the last 100 years (1906–2005) (Trenberth et al., 2007). The rate of warming over the last 50 years is almost double that over the last 100 years (0.13°C ± 0.03°C vs. 0.07°C ± 0.02°C per decade) (Trenberth et al., 2007). The trend is not linear, and the warming from the first 50 years of instrumental record (1850–1899) to the last 5 years (2001–2005) is 0.76°C ± 0.19°C (Alley et al., 2007). Current science is predicting increased global temperatures from between 1.8˚C and 6.6˚C by 2100, with current emissions pathways tracking at the higher end of the projections (Solomon et al., 2007, Garnaut 2008). In tropical areas, some areas will receive more rainfall while others will receive less. For Lesotho specifically, Kruger and Shongwe, 2004 and World Bank (2006) indicated that temperature is increasing at the rate of 0.1 to 0.3°C per decade, which is similar to decadal warming rates of 0.29°C in the African tropical forests (Conway et al., 2004, Kruger and Shongwe, 2004). In terms of rainfall, there would be both regional increase and decrease over land areas in the low latitudes (Boko et al., 2007).

Temperature and precipitation determine the carrying capacity of the biosphere to produce enough food for the human population and domesticated animals. The combined effects of increased temperatures and decreased rainfall are expected to cause significant changes in crop yields, cropping systems, scheduling of field operations and pest conditions (Chiotti and Johnston 1995). According to Boko et al., (2007), by the 2100s, a significant decrease in suitable rain-fed land extent and production potential for cereals is estimated under climate change. The wheat production is likely to disappear from African countries by the 2100s (Boko et al., 2007). Southern Africa would likely to experience notable reductions in maize under possible increased El Nino-Southern Oscillation conditions (Stige et al., 2006). Due to this, the crop production sector should be aware of efficient methods of water application and conservation for future (Semenov et al. 1995). Assessment of the effects of regional climate changes on agriculture might help to properly anticipate and adapt farming to maximize agricultural production (Benhin, 2006).

Climate change does not only affect agriculture. Agriculture has been shown to produce significant effects on climate change, primarily through the production and release of greenhouse gases such as carbon dioxide, methane, and nitrous oxide, but also by altering the earth's land cover, which can change its ability to absorb heat and light, thus contributing to radiative forcing (Adler et al., 2007). However, this fact is not within the scope of this study. This research is aimed at: (a) assessing, using crop simulation model, the relationships between crop yields and

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[1] Climate change as defined by UNFCCC is a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere, and which is an addition to natural variability that has been observed over comparable time periods (IPCC, 2007).

climate change, and (b) suggesting the adaptation measures that can implemented by farmers, the government and non-governmental sectors active in agriculture.

It is worth making distinction between climate and weather since this is often a confusing. Schulze *et al.* (1997) described climate as more than average weather for it includes the dynamic and intricate variations occurring diurnally, daily, monthly, seasonally and annually and also includes evaluations of extreme events and the variability about the mean. Whereas weather is the condition of the atmosphere at the particular time and place (Ahrens, 2008).

1.1: Background information

Lesotho has been practicing agriculture since ancient times. Lesotho's most important cereal crops like maize were introduced from Central America the Caribbean and Southern USA by the European explorers, mainly the Portuguese in the 16th Century (Magorokosho *et al*, 2007). In Lesotho maize, wheat and sorghum are the staple food for almost all the country's population and they are mostly planted by subsistence farmers under dryland farming. They are important source of carbohydrate, protein, iron, vitamin B, and minerals (IITA, 2002). In the past, there was little or no trade of agricultural products since people planted only for their own consumption (LMS, 2000). Gradually people began to realize that it was better for a farmer to grow agricultural crops for which suitable climatic conditions exist, and to exchange the excess of his produce with farmers from neighbouring areas with different climate (Dobie, 2008). This ultimately led to Agriculture being the foundation of Lesotho's economy. It accounts for about half of the national income and provides employment to about 75% of Basotho[2] (WPP, 2008).

However, despite being a very important sector to Basotho, production is primarily subsistence oriented and rainfed (AAC 2002). This means that any change in climate pattern would affect the production of different crops in the region. In recent decades, the world has witnessed that Lesotho agriculture has the slowest record of productivity increase in the world (Mendelsohn, 2000), probably due to climate change. For instance, Lesotho maize production for 2003 was estimated to be 150,000 tons from the area of around 180,000ha with the average yield of 0.8tons/ha. This value is very low compared to the South Africa's yield of around 2.9tonnes/ha. The problem is expected to be most severe since development technological changes for adaptation are slow (Mendelsohn, 2000). With an optimistic forecast of future development, FAO/WFP 2007, LVAC, 2007 estimate that between 400,000 and 550,000 food-insecure and vulnerable people (between 80,000 - 110,000 households) will require food assistance, with many households having already exhausted their cropping mechanisms.

Up to now, quite considerable number of researches has increasingly focused on examining the influence of climate change on crop water requirements and crop yields and estimating the impacts that are likely to occur under different warming scenarios globally and regionally (Betts 2005, Osborne 2005).

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[2] Basotho are the members of a subgroup of people who inhabit Lesotho.

1.2: Aim of the study

The major aim the study is to assess, using crop simulation and climate models, the relationships between crop yields and climate change and to suggest adaptation strategies in Lowlands of Lesotho, focusing on:

- cereal crops – sorghum, wheat and maize make up 85% of food production in Lesotho and are thought to be particularly sensitive to climate change (FAO 2003).
- estimating the responses of crop yields to greenhouse gas-induced climate change.

1.2.1: Research questions

- What are the likely impacts of climate change (precipitation, evapotranspiration and temperature) on crop yields under given specific climate change scenarios?
- What kind of adaptation measures can be suggested based literature and study results?

1.2.2: Specific objectives

In order to meet the main aim of the study, the following specific objectives are adopted:

- Use downscaled climate change data to determine how climate change affects crop yield, irrigation demands, growing season precipitation and temperature.
- To suggest various possible adaptation measures in agricultural practices that can be implemented by both government and its supporting organisations such as non-governmental sectors to ensure that people are food secure.

The results of this project are expected to alert the Government planners and other private sectors with forecasted crops yields so as to make effective decision concerning availability of food in the country and to make necessary preparations if there is a shortage of food.

1.3: Hypotheses

- Climate change has effects on crop yields in Lowlands of Lesotho.
- There are adaptation measures that the Lesotho government and farmers can implement.

1.4: Assumptions

- All yield figures used are for rainfed agriculture.
- Both climatic and crop yields figures are shown without error estimation.
- The growing season for maize, wheat and sorghum were taken from September to April the following year.
- No CO_2 fertilization effect.

2: CONCEPTS

2.1: Climate and crops

According to Moonen (2002), climate is one of the most important limiting factors for agricultural production: frost risk during the growing period and low and irregular precipitation with high risks of drought during the growing period, are common problems in agriculture. The critical agrometeorological variables associated with agricultural production are precipitation, and air temperature (Hoogenboom, 2000). De Jager and Schulze, (1977) suggests that climate is vital for the selection of correct crops for a given locality or site. The more detailed the knowledge about climate, the more intelligently the timing when they should be grown can be planned on macro-scale and the potential yields that may be expected can be predicted.

2.1.1: Temperature and precipitation

Generally, temperature determines the length of growing season of crops by determining the crops germination, vegetative and reproductive stages (FAO, 2009). Increased temperatures lead to increased evapotranspiration (Holmen, 2003) thus affecting water availability which is very important in the process of photosynthesis (Dawyer *et al*, 2006). Generally, high temperature affects the chloroplasts where photosynthesis takes place through generation of reactive oxygen species (Kreslavski *et al*, 2007). Low temperatures also affect crops by reducing their metabolic reactions (Sage & Kubien, 2007). Different crops have different optimum temperature:

- **Maize:** Bird et al., (1976), Kim et al., (2006), carried out experiments and observed that leaves from maize grown at 23°C photosynthesized faster than the leaves from maize grown at 13°C and 28°C.
- **Wheat:** Bird et al., (1976), McMaster et al., (2008), observed that leaves from wheat grown at 18°C or 13°C have faster rates of photosynthesis than leaves from wheat grown at 23°C or 28°C.
- **Sorghum:** Igyor et al., 1998, Bassam, (2010), observed that the optimum temperature for sorghum germination and development range from 25°C and 30°C. the minimum temperatures are 7-10 °C for germination and 15°C for development

Also precipitation must be taken into account since the magnitude and seasonal variation of either or both can limit the growth and development of crops (ICRISAT, 1980). According to Hoogenboom (2000), precipitation does not directly control any of the plant processes. It indirectly affects many of the plant growth and developmental processes. Decreased amounts of precipitation can cause an increase or decrease in developmental rates, depending on the stage of development and on species or cultivar (Nortes et al., 2009). Some species or cultivars are more drought-tolerant than others. Other weather factors (not considered in this study) that can affect crop yields include soil temperature, wind, and atmospheric humidity (Reason et al., 2005).

2.1.2: Crops- nonclimatic factors

Apart from climate factors crop yields are function of the following non- climatic factors like:

- **Edaphic factors**: soil erosion is a serious constraint, and has been a problem in many countries including Lesotho since early 1900s (FAO, 2003). The scarcity of agricultural land is compounded by volcanic soils, which are shallow, sandy, poorly structured and highly susceptible to erosion.

- Overgrazing and inadequate vegetative cover, all contribute to soil erosion and land degradation. Soil fertility is low.
- **Financial and technological factors**: Access to credit, market, transport, storage, infrastructure, fertilizer and high yielding seeds to small scale farmers. Credit facility in terms of cash is also important as it can help farmers to pay for extension services and transportation of final products to the market.
- **Cultural factors**: Economic experts have considered farming structure and land tenure systems as a serious handicap on increasing agricultural output (African Agriculture, 2010). It is argued the system represses instinct of self-interest and that it lacks sufficient incentives and fosters traditional subsistence farming.

2.2: Methods used in estimation of climate influence on crop yields.

Many Crop yields prediction methodologies have been developed to approximate yields before harvesting. They range from statistical methods, based on past associations between crop yields and climate, to dynamic methods, which attempt to represent the functioning of the crop under climate change (Slingo et al., 2005). Statistical methods on climate change studies have limitations because the statistical relationships that are valid today may not be valid in the future under changed climate (Jenkins & Lowe, 2003). In addition, the statistical models' complexity, their data demand, and method of analysis, often render them unpractical. The dynamic models can be highly sophisticated and have the capability of capturing non-linear behaviour and the impacts of weather variations on crop performance (Schlenker and Roberts, 2006). Apart from these methods, there is crop yields seasonal forecasting. This method is more mature than climate change prediction (Stone & Meinke 2005). Seasonal forecasting is also playing an increasingly key role in Famine Early Warning Systems (FEWS), particularly for Africa (Slingo et al., 2005). There is evidence that the effective use of seasonal forecasts and the associated development of sustainable adaptive strategies may help build resilience to climate change (Osbahr, 2007). However, they are based on ground-based visits and reports and often couched in probabilistic terms. Such reports are often product of subjective reporting of crop area and yield. This makes the estimation to be prone to large errors due to incomplete ground observations, leading to poor crop yield assessment and crop area estimations (FAO, 2003).

3: DESCRIPTION OF STUDY AREAS

3.1: Population

Lesotho has a total population of 2,067,000 (WPP, 2008) of which 70% live in fertile areas. It has a density of 188 persons per square meter (Bureau Of Statistics (BOS), 2008). Lowlands of Lesotho cover an area of with a population of 500,000 in Maseru, 450,000 in Leribe and 310,000 in Mohales'Hoek (WPP, 2008). In these three districts the population of 30% in Maseru, 60% in Leribe and 40% in Mohales'Hoek are farmers and agricultural labourers (WPP, 2008). The rest are employed in other small scale trades**.**

3:2: Location

The lowlands of Lesotho are located in the western site of Lesotho with a total landmass area of about 5000 km^2 (Hydén, 2002). The lowlands have a north-south extension of 200km (figure.1). The region is one of African land areas located to the Southern part of the Equator. It is between the longitudes 27°00' and 29°30'E and latitudes 28°35' and 30°40'S (FAO, 2007).

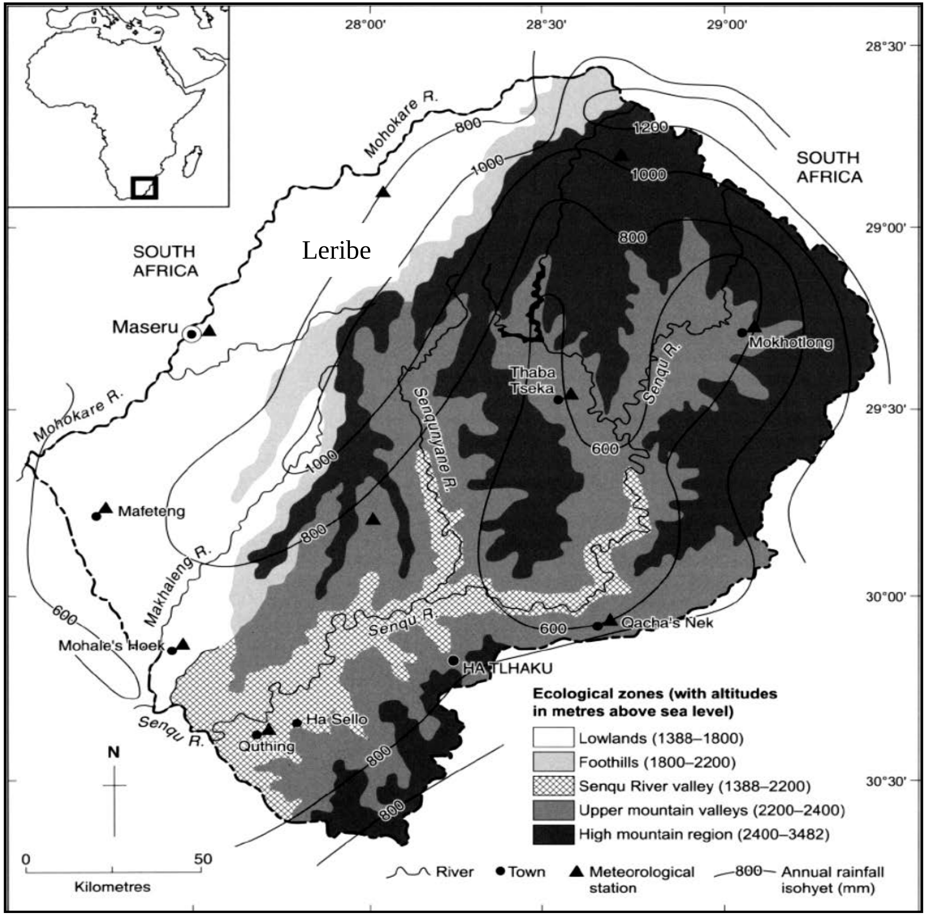

Figure 1: Topographic map of Lesotho and location of weather stations. (Ziervogel, 2004)

3.3: Climate

Rainfall and Temperature patterns

The climate is primarily influenced by the country's location in the Karoo basin, spanning altitudes ranging from about 1400m to about 3480m above sea level (LMS, 2000). Precipitation is highly variable both temporally and spatially. It has been shown that there is a strong significant influence of both the warm Indian current from Indian Ocean and the cold Benguela current from the Atlantic Ocean (Todd et al., 2004; Todd and Washington, 1999). Hydén, (1996a) also found out there is strong correlation between Lesotho Lowlands regional rainfall and rainfall over much larger summer rainfall region of South Africa. The region has four seasons:

- Summer (November, December, January), with temperatures of 27-30 °C
- Autumn (February, March, April), with temperatures of 9.5- 25°C
- Winter (May, June, July), with temperatures of -10 to 12 °C
- Spring (August- October), with temperatures of 11-22°C

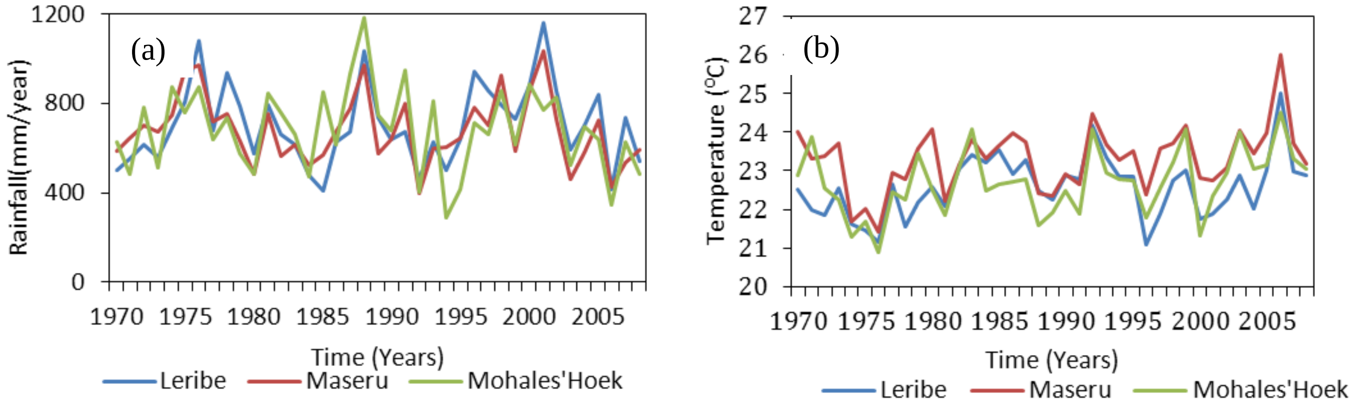

Figure 2: (a) Annual rainfall and (b) temperature (1970-2008).

Winters are generally cold, characterized by domination of high-pressure systems with the resulting clear skies and precipitation is mainly in the form of snow and very low if any (LMS, 2000). Extremes of monthly mean winter temperatures of -10°C can be reached and daily winter minimum temperatures can drop as low as -21°C (LMS, 2000). Summers are hot and humid due to the proximity of ITCZ and Kalahari low-pressure area which draw in land, the moist tropical air masses from the Congo basin (LMS, 2000).The highest mean maximum temperatures ranging from 16.5°C to 30°C are recorded in January.

The average annual rainfall ranges between 500mm to 1200mm (LMS, 2000). Most of the rainfall comes in the seven-month period from October to April and peaks from December to February. In the past years Lesotho has experienced three droughts (1983-84, 1992-94, and 2006-2007 seasons) of varying severity (LMS, (2000). Of these three incidences, the 2006/07 cropping year experienced the most severe droughts in the last 30 years. Overall, drought conditions coupled with excessive heat have a negative impact on agriculture (crops and livestock), food and water availability. Figure 2 shows present rainfall distribution in representative districts for lowlands of Lesotho namely, Leribe, Maseru and Mohales'Hoek. These districts are known of:

- The north area represented by Leribe with high values of rainfall and very good yields (3.63-4.55mt ha^{-1})
- The central area represented by Maseru, with medium values yields (1.45- 2.24mt ha^{-1}).
- The southern area represented by Mohales'Hoek, with and acceptable yields (1.2-2.79 mt ha^{-1})
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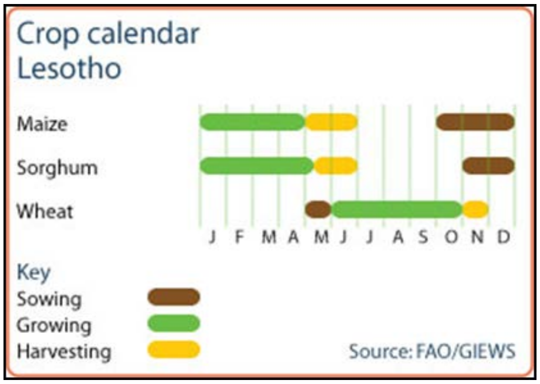

Figure 3: Traditional cropping calendar in the study areas.

3.4: Soils of study area

Only around 15% of the country is arable and the rest is composed of rocky land as well as steep slopes (Jayamaha, 1979). In most parts of the country, soils are deficient in nitrogen (N), phosphorous (P) and occasionally potassium (K) (Marake, 1999). In dry areas, where rainfall is low, variable, unreliable and unevenly distributed, the soils have little organic matter (LMS, 2000). Schmitz and Rooyani (1987) reported that seven out of eleven benchmark soils of Lesotho had an acidic soil reaction and most of them were from the lowlands and lower foothills. The most recent national mapping gives three dominant soils as Alfisols, Mollisols and Entiosols according to the USDA soil Taxonomy classification system (Soil Classification Working Group, 1991). They are particularly erodible soils with severe management problems.

3.5: The present agricultural sectoral performance

Lesotho's agricultural year runs from August to July with harvests from winter being wheat in the first half of the year and maize, sorghum and wheat in the second half. The main growing season starts in January and lasts until May. The second growing season is in June to October. Wheat is the main crop during this period. Figure 3 shows the relevant cropping calendar.

The three main cereals grown in Lesotho are maize, wheat and sorghum. They account for 77% (85% according to FAO (2003)) of the country's cereal production (LMS, 2000). Currently they appear to be declining especially in lowlands (FAO 2003) as depicted in figure 4. But cropped area is increasing. Their contribution to Lesotho's GDP has fallen from 30% in the 1980s to less than 20% (Mayet, 2005). Figure 4 shows that from the year 1994/5 to 1995/96 area planted with three crops increase and slightly decline to the year 1996/97. Maize, sorghum and wheat yields in metric tonnes per hectare follow the same tendency. Crop yields dropped significantly in the 1990/91 growing season. Overall crop yields declined from 0.74 metric tonnes per hectare in 2005/06 to 0.42 metric tonnes per hectare in 2006/07 (FAO, 2009). The depressed crop yields and casual labour opportunities, coupled with very high increases in the price of maize (staple) led to about 553, 000 households not being able to meet their annual food entitlements in addition to not being able to meet essential expenditures (LVAC, 2007). Although maize production is declining as it can be seen from figure 4 above, it still remains the country's staple food, constituting an estimated 80% of the rural diet (FAO, 2009).

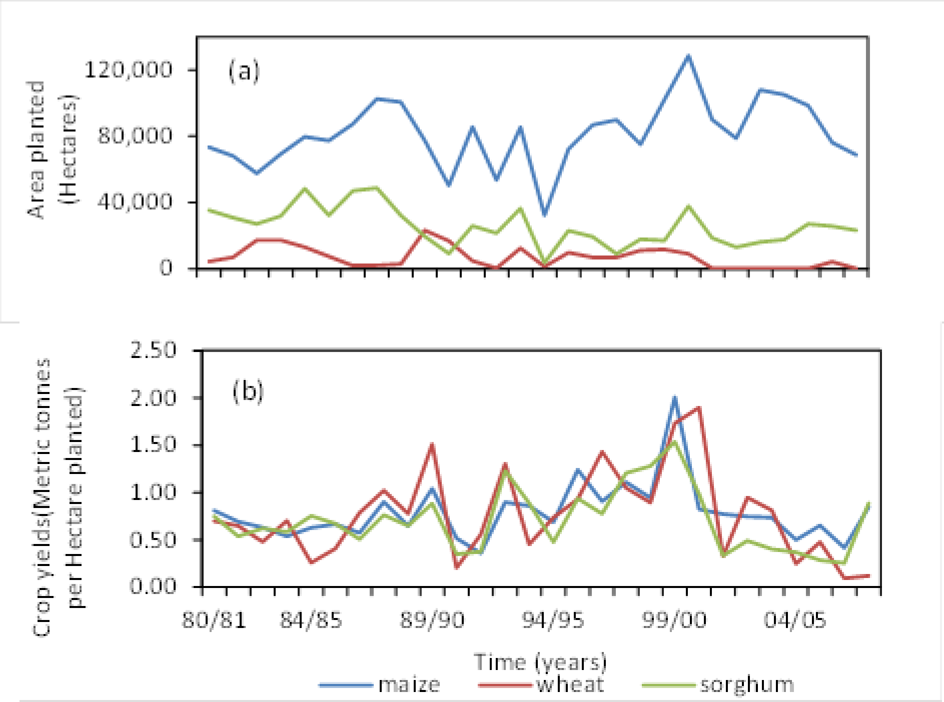

Figure 4: (a) Area planted and (b) Crop yields patterns for Lowlands of Lesotho since 1980.

3.6: Traditional Yields estimation in Lesotho

Various techniques are used in order to determine the yield per unit area of each crop by BOS and NGOs. These include household interviews, crop samples (cuts), visual observations of growing crops, closer evaluation of yields of harvested crops and grain storage tanks, counting of plant population densities and discussions with agricultural extension workers and individual farmers. Available historical data including the national average yields were also used in the determination of the yields. Another technology involves a complete enumeration for crop acreage and sample survey based on crop cutting experiments.

The crop acreage and corresponding yield estimate data are used to obtain production estimates. Final production estimates based on this sampling method becomes available after the crops are actually harvested. Large enumeration areas constitute Primary Sampling Units (PSUs). Individual agricultural holdings (farming households) constitute secondary sampling units (SSUs) for estimation of land use, crop areas and livestock population. Fields under maize and

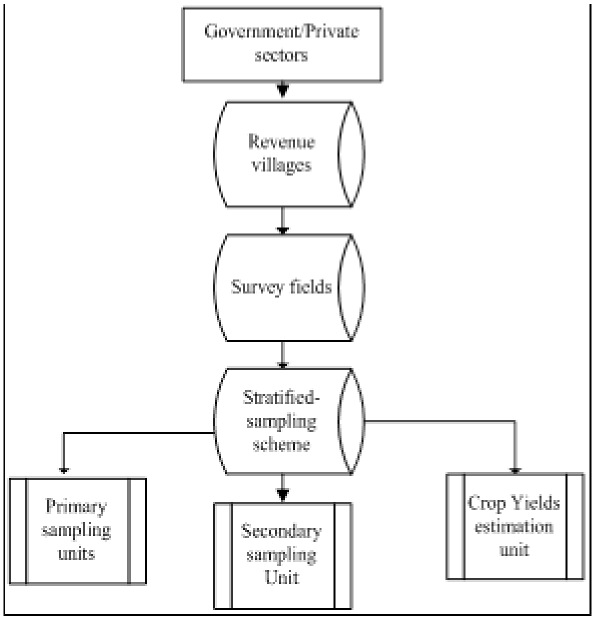

Figure 5: Sampling design for BOS.

sorghum formed the third sampling units for estimation of crop yield. Two subplots for crop cutting in each selected field formed the ultimate units for yield estimation (Crop Forecasting, 2008).

4: METHODS AND MATERIALS

In an attempt to assess the extent to which Lowlands of Lesotho are vulnerable to climate change, an analysis of the current climate is made together with an analysis of the elaborate relationship which exists between climate and crop yields. The analysis involves the development of a number of climate scenarios[3], the use of simple climate model (MAGICC/SCEGEN) and crop model (CROPWAT). The output will give likely changes in crop yields as result of increasing or decreasing temperature and precipitation.

This detailed analysis is made in a step-wise manner. First, it involves the description of baseline data, climate model, emissions scenarios and selection and evaluation of GCMs. The second step involves the description of crop model and its calibration. Last, the potential impacts of the climate scenarios are then be assessed across different crops.

4.1: Historical climate data

Monthly observed climate data (precipitation, maximum and minimum air temperature) records have been made available through Lesotho Meteorological Services for the three stations namely Leribe, Maseru and Mohales'Hoek in the Lesotho Lowlands, for the 38-year period 1970-2008. The rare gaps in the records have been filled with data from adjacent rainfall stations in South

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[3] According to Fischer et al., (2005), a climate change scenario is "a physically consistent set of changes in meteorological variables, based on generally accepted projections of the atmospheric concentrations of CO_2 and other trace gases".

Africa, for which data has been provided by the South African Weather Bureau. The quality of data has been checked and found adequate by Lesotho Meteorological Services. The data is analysed for the entry into the crop simulation model.

Evapotranspiration (ETo) is an indicator of a plant satisfaction, incorporating the moisture that would evaporate from a land surface and transpiration from a plant under no internal stress. It is a function of precipitation, temperature, radiation, wind and humidity. But due to some data limitations, in this study it is calculated using Hargreaves' Equation (Hargreaves, 2003), which is stated as follows:

$$\boldsymbol{ETo = 0.0023 S_o (T + 17.8)\sqrt{\delta_T}} \qquad \mathbf{(1.1)}$$

where:

T = Mean temperature (° C)

δ_T = difference between mean monthly maximum temperature and mean monthly minimum temperature (° C)

S_o= the water equivalent of extraterrestrial radiation [mm d^{-1}] for the location:

$$So = 15.39 d_r(\omega_s \sin\emptyset \sin\delta + \cos\emptyset \cos\delta \sin\omega_s) \qquad (1.2\ )$$

φ = latitude of the site (+ in northern hemisphere, - in southern),

ω_s= the sunset hour angle (radians):

$$\omega_s = \arccos(-\tan\emptyset \tan\delta) \qquad (1.3)$$

δ = solar declination on day J (Julian day) of the year [radians]:

$$\delta = 0.4093 \sin(\frac{2\pi}{365} J - 1405) \qquad (1.4)$$

d_r= relative distance of the earth from the sun on day J:

$$d_r = 1 + 0.033 \cos(\frac{2\pi}{365} J) \qquad (1.5)$$

The linear trend fitting analysis of observed data is also performed. This method calculates the best fitting line for the observed data by minimizing the sum of the squares of the vertical deviations from each data point to the line. The equation of a linear regression line is given as:

$$Y = a + bx \qquad (1.6)$$

Where, *y* is the observation on the dependent variable

x is the observation on the independent variable

a is the intercept of the line on the vertical axis and *b* is the slope of the line.

The correlation coefficient to determine the strength of linear relationship between temperature, rainfall and yields is computed.

4.2: Climate model description

The climate model is used to project changes in average rainfall, and monthly temperature for the region for two time slices (near-term and long-term). The name of this model is MAGICC-(Model for the assessment of greenhouse-gas induced climate change). It is a set of linked models. It falls in the genre of Simple Climate Model as defined by Harvey et al., (1997).

MAGICC is not a GCM, but it uses a series of reduced-form models to emulate the behavior of fully three-dimensional, dynamic GCMs (Hulme et al, 2008).

SCENGEN – a global and regional SCENario GENerator – is not a climate model; rather it is a simple database that contains the results of a large number of GCM experiments, as well as an observed global and regional climate data sets (Hulme, 2008). These various data fields are manipulated by SCENGEN, using the information about the rate and magnitude of global warming supplied by MAGICC and directed by the user's choice of important climate scenario characteristics (Hulme et al., 2008). Characteristics like gas cycle model, global-mean temperature and sea- level model. SCENGEN reports current and changes in regional climate in 2.5° by 2.5° grid boxes. For this study, the grid box is enlarged and adjusted to the west of Lesotho because the Lowlands of Lesotho are close to the western edge of its grid box. The area modeled ranged between the longitudes 27°00' and 29°30'E and latitudes 28°35' and 30°40'S.

4.2.1 Global climate Model Selection for Lowlands of Lesotho.

According to Tubiello (2002), it is very important not to depend on one GCM alone, but several climate predictions when developing assessment studies for impacts of climate change on crop yields. Based on this, four GCMs are used namely Canadian Centre for Climate Modeling & Analysis (CCCMA), Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GISS-EH), and Hadley Centre for Climate Prediction and Research (UKHADCM3). These are sophisticated models that include the radiative effects of minor greenhouse gases as well as CO_2, and water vapour (Eyring et al., 2005a). These GCMs have been successfully used to evaluate climate change impacts on runoff and agriculture in Lesotho (LSM, 2000). Due to computational constraints and input data availability, these GCMs typically have a large spatial resolution, where each grid cell covers several degrees of latitude and longitude as shown in table 1 below. The normalized changes of model by model as opposed to weighted changes are used since they have the advantage of factoring out uncertainties in the climate sensitivity, allowing the models to be considered separately (Bony, 2006).

Table 1: Resolution of the GCMs (Wigley, 2008)

GCM	Country of origin	Approximate Resolution (lat.× long)
CCCMA-31	Canada	4°× 5°
GFDL-21	USA	2.25°× 3.75°
GISS-EH	USA	4° × 5°
UKHADCM3	UK	2.75°× 3.75°

4.2.2 Model selection criteria

The following criteria are employed to assess the applicability of the GCMs based on their ability to reproduce observed seasonal and monthly patterns of mean temperature and rainfall over the lowlands of Lesotho for a 29-year period (1980-2008). And hence being able to create optimised future climate change scenarios for Lowlands of Lesotho:

a) **Validity:** Firstly it is assumed that the GCM that simulates well the current 1980-2008 climate of Lesotho will also better represent the future climate of the country. Two statistical metrics, correlation analysis and root mean square error, are used measure of model performance. A pattern correlation coefficient of 1.0 indicates a perfect match between the observed and simulated spatial pattern, and a root mean square error of 0.0 indicates a perfect match between the observed and simulated magnitudes.

b) **Resolution:** The other factor is to choose a model that has a higher resolution. Higher resolution models with dense grid contain spatial details and some key processes of climate variability such as ENSO events are better represented. Such model should also provide a more realistic representation of geographic climate features of the country. This criterion deserved special attention since Lesotho has a mountainous terrain.

4.3: Climate change and GHGs emissions scenarios.

In order to cover the influence of future greenhouse gas emissions and the corresponding socioeconomic development, a range of future greenhouse gas emission scenarios have been defined by IPCC in their Special Report on Emission Scenarios (SRES) (Xiong et al., 2007). In this study, A2 and B2[4] SRES emission scenarios[5] are selected as they are found to be relevant for developing countries (Christensen et al., 2007, Doria et al., 2007; Zhang et al., 2007; De Silva et al., 2007). The decision on their relevance is based on population growth, economic development, technological innovation, energy consumption, land-use, agricultural development, and environmental policy of developing countries. However, the SRES scenarios considered herein have recently been criticized for their regional economic growth patterns, regarded as too strong when compared to historical data (Nakicenovic et al. 2003). In addition, SRES A2 is regarded as having population growth rates beyond the current UN high projections (Fischer et al., 2005). The results obtained under this socio-economic path may thus be regarded as providing a *worst case scenario* for the crop yields analysis.

The use of climate change scenarios, built from the results of GCM simulations, has been at the core of climate change assessments on agricultural and water resources (Rosenberberg, 1992). In this study, climate changes are estimated as follows: A2 and B2 difference in mean temperature and precipitation for 2030-2050 (near-term), 2080-2100 (long-term), and historic averages (1980-2008) are predicted. In the final step Temperature changes for each GCM are added to the mean monthly temperature for the stations base period 1980-2008 to yield future temperature scenarios. Precipitation scenarios are created by adding changes for the years 2050 and 2100 as created by each GCM to the long-term precipitation averages for base period 1980-2008 based on precipitation. The scenarios that are estimated included future monthly, seasonal temperature and precipitation changes for the years under consideration.

4.4: Climate model evaluation.

The evaluation of the model is carried out to be able to establish relationships between spatially adjusted GCMs data and the weather variables at stations-level. Here, the simulated region measurements are selected by taking the grid-point value in which a given region is found and

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[4] A2: describes a very heterogeneous world with continuous increasing in world's population, slow economic development and medium-high rise in greenhouse gas emissions

B2: regional sustainable development, with slower increase in the world's population and a medium-low rise in greenhouse gas emissions.

[5] SRES emission scenarios are images of how the future might unfold in terms of Greenhouse Gases emissions (Nakicenovic, 2000).

assigning that value to the simulated estimate. Differences are then taken between the simulated estimate and the observed value. This provided insight into the components that needed to be adjusted for better results. The period of analysis is 1980-2008 for both temperature and precipitation stations.

4.5: CROPWAT yield estimation

In order to address the research questions of this paper, namely the impacts of climate change on crop yields, an assessment is done. This is carried out using CROPWAT simulation model (FA0, 2006). The CROPWAT model (FAO, 2006) is selected for use in this study on the basis of previous tests and satisfactory performance in number of world-wide locations under varying climate circumstances (Allen et al., 1998). The assessment mainly involves estimation of potential changes in crops physiological responses (yields, evapotranspiration, and irrigation demands) under the combined impacts of climate change, in particular higher temperature, and modified rainfall patterns with respect to current climate conditions.

4.5.1: CROPWAT description

The latest version of model, namely CROPWAT v8 includes a simple water balance model that allows the simulation of crop water stress conditions and estimations of yield reductions based on well-established methodologies for determination of evapotranspiration (FAO, 2006) and yield responses to water. This model utilises soil, crop, and weather databases to simulate multi-year outcomes of climate change scenarios and various crop management strategies. The model also allows the development of recommendations for improved irrigation practices. More details on the stated methodologies are provided below. As an indication of water stress, irrigation requirements are computed. This modeling work took into account the variables shown in table 2 below:

4.5.2: Data requirements for CROPWAT

Table 2: The input and output of the CROPWAT model (Stancalie, 2010).

Data	Input	Output
Climatic	-Monthly rainfall data -Monthly mean minimum temperature (°C) -Monthly mean maximum temperature (°C) -Potential evapotranspiration	-Crop water requirement -Irrigation requirement
Crop	-Sowing date -Crop coefficient -Crop description: according to observed crop phenology -Percent (%) area covered by plant	-actual crop evapotranspiration
Soil	-Initial soil moisture condition -Maximum root infiltration rate -Maximum rooting depth (1m)	-Daily soil moisture deficit
Irrigation	-irrigation scheduling criteria	-irrigation scheduling -estimated yield reduction due to crop stress

Table 3: The CROPWAT soil input (FAO, 2006)

Sites	Soil type	Maximum rooting depth (cm)	Total available soil moisture (mm/meter)	Maximum rain infiltration rate (mm/day)
Leribe	Red loamy	900	180	30
Maseru	Sandy	900	100	30
Mohales’Hoek	Sandy-clay	900	130	30

4.5.3: Planting dates

For the length of crop development, values of days for the four distinct growth stages used in simulation were taken from Allen (1998). The same dates of sowing and harvesting were used for each of the three selected districts of Leribe, Maseru and Mohales’Hoek. The total cropped areas for each crop, and maximum crop yields (maize, wheat, sorghum) for each district are provided by the Lesotho Agro-meteorological Services.

Table 4: Planting date, harvesting date and length of growing stages (days) for selected crops in study sites.

		crop growing stages (days)				
Crop	Planting date	Initial	Development	Mid-season	Late season	Harvesting dates
Maize	30/October	40	65	75	60	30/June
Wheat	30/April	40	65	75	60	15/November
Sorghum	30/October	30	65	75	55	15/May

4.5.4: Determination of crop water requirements.

Estimation of the crop water requirement is derived from crop evapotranspiration (crop water use) which is the product of the reference evapotranspiration (ETo) and the crop coefficient (Kc) (see equation 1.6). The reference evapotranspiration (ETo) is estimated based on the Hargreaves method, using temperature data as stated earlier.

$$\mathrm{ETc} = \mathrm{Kc} \times \mathrm{ETo} \qquad (1.6)$$

Where ETc = Crop evapotranspiration

Kc = Crop coefficient

In this research, the crop coefficient (Kc)[6] values used in the crop simulation were taken from FAO.

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[6] Kc is defined as the ratio between the maximum water loss of cultivated crop as a given stage in it growth and either the potential water loss or some reference water loss (Allen et al,, 1998)

Table 5: Kc for different crop growth development.

Crop	Crop growth stages		
	Initial	Development & Mid-season	Last-Season
Maize	0.45	1.5	0.5
Sorghum	0.2	0.55	0.45
Wheat	0.2	0.65	0.55

ETc in equation (1.6) is computed from crops grown under optimal management and environmental conditions. However, given that in most instances crops are not under optimal conditions, the actual ETc (ETa) in this research is calculated by using a water stress coefficient or by adjusting Kc for different stress and environmental constraints (Equation 1.7).

$$\mathrm{ETa} = \mathrm{Ks} \times \mathrm{ETc} \qquad (1.7)$$

Where, water stress coefficient (Ks) is as a function of total available water (TAW[7]), readily available water (RAW[8]) and depletion from the root zone (Dr).

$$\mathrm{Ks} = \left(\frac{\mathrm{TAW} - \mathrm{Dr}}{\mathrm{TAW} - \mathrm{RAW}}\right) \qquad (1.8)$$

Although monthly climatic data are input, the output ETc is expressed daily in mm per day. The monthly values are converted in to daily values using polynomial curve fitting model. The average values of crop coefficient for each time step are estimated by linear interpolation between the Kc values for each crop development stage.

4.5.5: Yields-Moisture stress relationship

Prediction of reduction in yields is achieved by employing a simple, linear crop-water production function, introduced previously by Stewart *et al.* 1977. This formula enables the degree of sensitivity to water to be taken into account in estimating yield reductions for various crops and growth stages based on the soil moisture status. The main indicator of water shortage is Actual evapotranspiration (ET_a) as shown by the equation below:

$$\left(1 - \frac{\mathrm{Ya}}{\mathrm{Ym}}\right) = \mathrm{Ky}\left(1 - \frac{\mathrm{ETa}}{\mathrm{ETc}}\right) \qquad (1.9)$$

$$\text{Yield decrease (Ya)} = \mathrm{Ym} - \mathrm{Ky}\left(1 - \frac{\mathrm{ETa}}{\mathrm{ETc}}\right)\mathrm{Ym} \qquad (1.10)$$

Where Y_a is actual crop yield

Y_m is the maximum crop yield (obtained from statistical data) (metric tonnes/ha)

K_y is the yield response coefficient (dimensionless)

ET_a actual evapotranspiration (mm/dec)

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[7] TAW: this is the amount of water that a crop can extract from its root zone. It is taken as the range between field capacity and permanent wilting point (Allen, 1998)

[8] Raw: is the fraction of TAW that crop can extract from the root zone without suffering stress (Allen, 1998)

ET_c is the maximum Crop evapotranspiration (mm/dec)

Crop response factors (Ky) relate the relative yield decrease to the relative evapotranspiration deficit caused by a lack of adequate water. The Ky[9] (yield response coefficient) factor from the FAO (1998) was used for each crop as shown in table 6 below. These Ky values are obtained through empirical experiments. A crop yield response factor, greater than one, indicates that the yield decrease is proportionally greater than the associated relative difference between the potential and actual evapotranspiration (Allen, 1998). Therefore, crops with a crop yield response factor (Ky) lower than one can generate less yield decreases.

Table 6: Yield Response Coefficients (Ky) (Allen et al., 1998).

Crop	Ky
Maize	1.25
Sorghum	0.9
Wheat	1.15

4.6: Irrigation requirements

The amount of water required to compensate for the evapotranspiration loss from the cropped field is defined as the crop water requirements (CWR) (Allen, et al., 1998) is also estimated. The irrigation water demand represents the difference between the crop water requirements and the effective precipitation (Allen, et al., 1998). For irrigation requirements, the monthly total rainfall has to be distributed by equivalent daily values. CROPWAT achieves this in two steps. First, rainfall the month-to-month rainfall is smoothed in a continuous polynomial curve. The effective rainfall is calculated automatically in the files with rainfall data. The United State Department of Agriculture-Soil Conservation Services (USDA SCS) method which is set as the default in the model for calculations of irrigation requirements is used. The equations employed in this method are as follows:

$$\mathrm{Fn} = \mathrm{ETc} - \mathrm{Pe} - \mathrm{GW} - \Delta\mathrm{SW} \qquad (2)$$

Where: Fn = Irrigation demands

Pe = effective rainfall, mm

ETc = Crop evapotranspiration (mm)

ΔSW =change in soil water in the crop root zone (mm)

GW= Groundwater contribution to evapotranspiration during growth period (mm/dec)

4.7: CROPWAT calibration

The CROPWAT model is calibrate using local experimental crop data and observed climate data from 1990-2008 collected from Agro-meteorological sector in Lesotho. The crop data includes aspects like planting dates, growth analysis, harvesting date and final yield components. In this

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[9] Ky quantifies the response of yield to water. The Ky values for most crops are derived on the assumption that the relationship between relative yield and relative evapotranspiration is linear and is valid for water deficits of up to about 50 percent (FAO, 2007).

study, three stations to calibrate the CROPWAT model are used. They are Leribe, Maseru, and Mohales'Hoek.

Flow chart of methodology

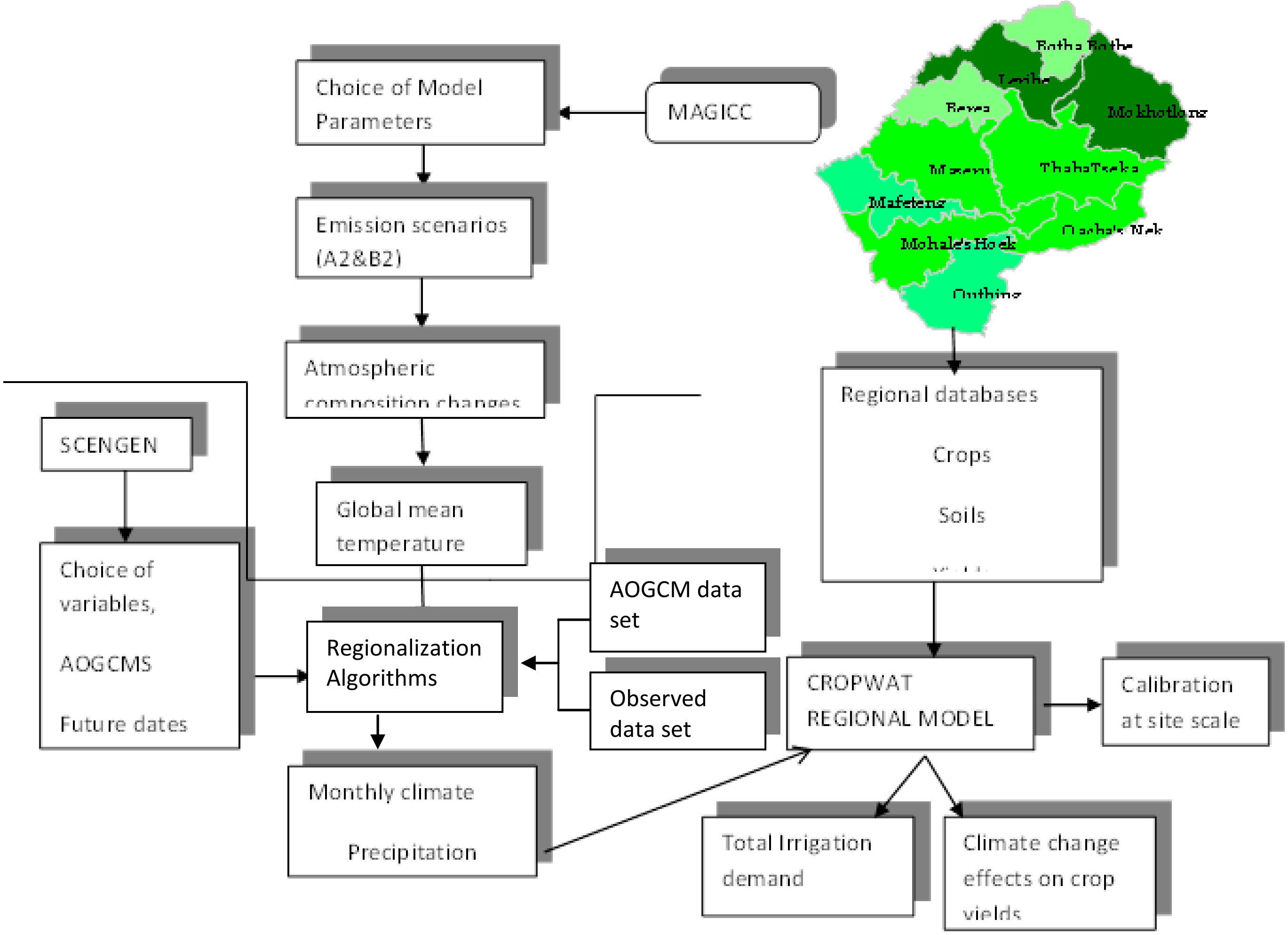

Figure 6: Interaction of the Models used in the study for data analysis.

4.8: Limitations of the models.

To better interpret the results obtained through the use of these models, one needs to be aware of the many uncertainties that could not be addressed. The following variables were not captured:

Crop model

- **Pests and diseases.** The potential effects of climate change on crop damage due to pests and diseases was not considered in the study and assumed to remain at the current level. At present damage is estimated to reduce potential global crop yields by 30% each year (Wolfe et al., 2008).

- In the crop model simulations, nutrients are not limiting and weeds. All these assumptions tend to overestimate simulate yields.
- With regard to simulating the impacts of climate change on cropping systems, the model study is limited because technology and climatic tolerance of cultivars are held constant even though both are likely to adapt to changing climate.

Climate model

- **Resolution:** it is well known that GCM projections present significant uncertainties, due in part to issues of scale resolution, leading to incomplete model representation of regional climate systems; and in part to imperfect understanding of key climate dynamics, such as water vapour–cloud feedbacks (Fischer et al., 2005).
- **Climatic variability:** The clarified role of the different teleconnections and feedback mechanisms (e.g ENSO-precipitation relationships) (Saji et al. 1999, Webster et al. 1999) in modulating African rainfall variability are not well replicated by the GCMs in this region. Increased seasonal or annual climatic variability as well as variability across small geographic areas is expected to go hand-in-hand with broader worldly trends in temperature increase (Rosenzweig, 1993).
- **Extreme weather events.** Climate change is predicted to affect the frequency and severity of extreme weather events such as cyclones, hurricanes, and prolonged droughts. Extreme weather events can result in significant crop losses from wind damage, flooding, or inadequate soil moisture (Rosenzweig, 1993). Although it is recognized that extreme weather will affect future yields, it is very difficult to model such events in a way that provides realistic assessment of their yield impacts (Rosenzweig, 1993, Soussana, 2010).
- The inability of climate model predictions to account for the influence of land cover changes on future climate.

5: RESULTS AND DISCUSSION

5.1: Historical climate and yields data.

5.1.1: Temperature, rainfall Crop yields patterns analysis

The temperature, as it is imperative from current data, is increasing. The mean minimum **(**T*min***)** and mean maximum **(**T*max***)** temperatures follow an increasing trend that signifies the impact of climate change over the study area. The results of linear trends thus obtained, are summarized in table 7 and main features are discussed below: The rate of increase in the minimum temperature of Maseru leads the rest, having a value 0.06ºC per year (table. 7) (fig.7). The maximum temperature of Mohales'Hoek shows least increment among all i.e. 0.02ºC per year. Most of the temperatures of considered districts have rates of increase that lie within 0.01ºC to 0.06ºC per year. The mean maximum temperature of Maseru and Leribe have same rate of increase, as it is evident from table 7 and (figure7).

The analysis of the events of rainfall indicates that Leribe received heavy rainfall during a number of years during the 1980-2008 period (figure 2). A quadratic trend analysis is also attempted apart from linear trend analysis. However, it showed no significant improvement in the results. The linear trend analysis is found to be sufficient to extract the general rising tendency of temperatures.

For crop yields, none of the studied sites indicate a positive slope coefficient. The magnitude of these negative slopes gives an implication that crop yields are leveling off in Maseru and Mohales'Hoek over this period but for Leribe the coefficient is low symbolising that climate has been more or less favourable over the period.

Table 7: Linear trend equation for decrease in crop yields for studied sited, 1980-2008.

	Linear trend equation			
Site	Yields	T_{max}	T_{min}	Rainfall
Leribe	$y = -0.001x + 0.66$	$y = 0.03x + 22.4$	$y = 0.04x + 7.9543$	$y = 6.32x + 608$
Maseru	$y = -0.01x + 0.77$	$y = 0.03x + 22.4$	$y = 0.06x + 7.0743$	$y = 0.63x + 678$
Mohales'Hoek	$y = -0.004x + 0.84$	$y = 0.02x + 23.1$	$y = 0.04x + 7.5663$	$y = 1.32x + 709$

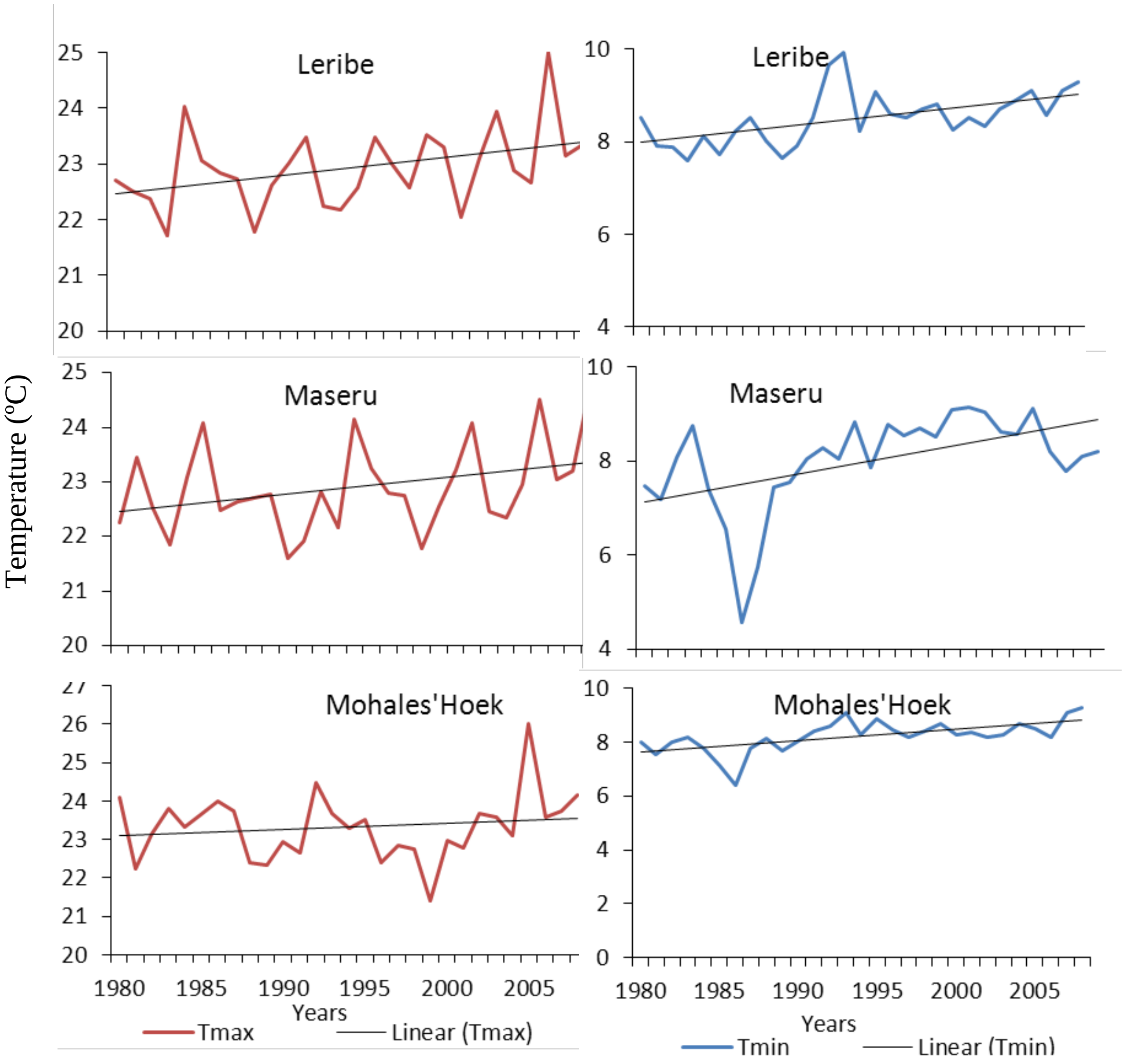

Figure 7: The temperature trends for all studied sites.

5.1.2: Effects of temperature and rainfall on crop yields.

Previous studies have demonstrated, at the scale of the entire lowlands of Lesotho, that Climate is the most important factor in agriculture in general, and in crop production in particular (Low & Rebelo, 1996). Annual rainfall, temperature and annual crop yields are analysed. Table 8 shows the results of the crop yields-rainfall, temperature regressions for all selected districts.

Table 8: R^2 and Slope derived from the Crop yields-rainfall, temperature regression for study sites (1980-2008)

	Rainfall			Temperature		
Site	R^2	Slope	P-value	R^2	Slope	P-Value
Leribe	0.50	191	<0.001*	0.05	0.2	0.260
Maseru	0.48	547	0.005*	0.09	0.7	0.111
Mohales'Hoek	0.21	238	0.064	0.03	-0.4	0.105

**Statistically significant*

For two of the three districts, the relationship between crop yields and rainfall is significant but not strong. Leribe shows the best relationship with R^2 = 0.50 and slope (S) of 191 while for temperature it shows R^2 = 0.05 and S= 0.21. Maseru shows a relationship with R^2 = 0.48 with S = 547 while for temperature the site shows a weaker relationship with R^2 = 0.09 and with S= 0.7. The relationship between crop yields and rainfall for Mohales'Hoek located in southern part of lowlands is weak with R^2 = 0.21 and with negative slope for temperature S = -0.4.

Through regression analysis it is observed that annual rainfall of one site and annual crop yields is weakly correlated. For two sites annual rainfall and annual crop yields are well correlated. This could imply that a change in crop yields is due to other factors than rainfall and temperature. However, slope as the measure strength and direction of relationship tends to be positive for rainfall in all sites implying that an increase in crop yields is associated with an increase in annual rainfall. The same behavior is observed with slopes for temperature except for Mohales'Hoek district with negative slope. This negative slope implies that temperature depressed yields over this period. It is also important to note that the use of annual mean rainfall could have caused a poor correlation as not only total annual precipitation but also the intensity of single rainfall events play an important role in the occurrence of crops (Tucker, 1991). This does not hinder the fact that rainfall can certainly said to be one of the possible causes of changes in crop yields. However, implying that this is the only factor involved may be a simplification, as change is due to the effect of a combination of driving forces such as fertilizer application, soils conditions, pests and other pathogens. In addition, occurrence of dry spells is correlated with crop yields of Lesotho (LMS, 2000). Making the comparison between crop yields and precipitation thus requires local knowledge of the variability of these two.

5.1.3: Reference evapotranspiration

Reference evapotranspiration figures have been worked out, and turn out to be higher than normal rainfall. This indicates that moisture availability is an important concern in agricultural activities in Lowlands of Lesotho.

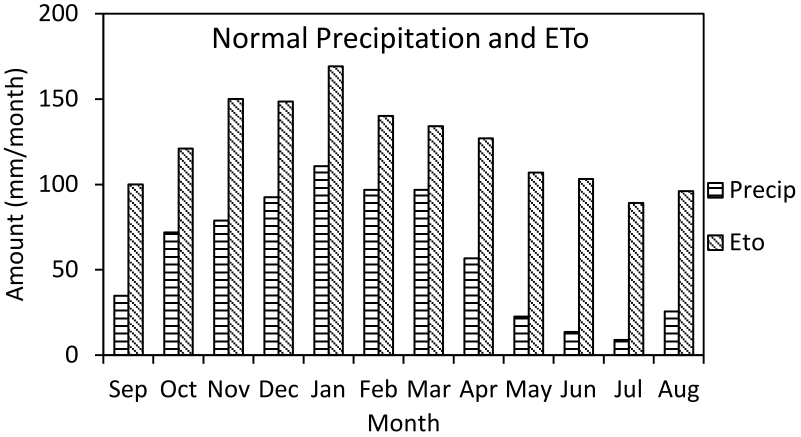

Figure 7: Comparison of monthly precipitation and referenceevapotranspiration.

Reference evapotranspiration is higher than precipitation throughout the year. Lowlands of Lesotho can be classified as dry.

5.2: Selection of applicable global climate models.

Following the criterion of comparing the average simulated temperature and rainfall with observed data, it is found that among the four GCMs, the GFDL model followed by the UKHADCM3 model closely simulates the current climate of the country as illustrated in figure 8. It is observed that precipitation and temperature were generally highly overestimated by GISS-EH and CCCMA as compared to the GFDL and UKHADCM3. From table 9 and resolution of GCMs (table 1). It is also visualized that the GFDL and the UKHADCM3 models will be more ideal compared to other models in creating future climate scenarios for Lowlands of Lesotho. Therefore, it can be recommended that more weight can be given to the GFDL and the UKHADCM3 models in undertaking climate change impact assessments on crop yields of Lowlands of Lesotho.

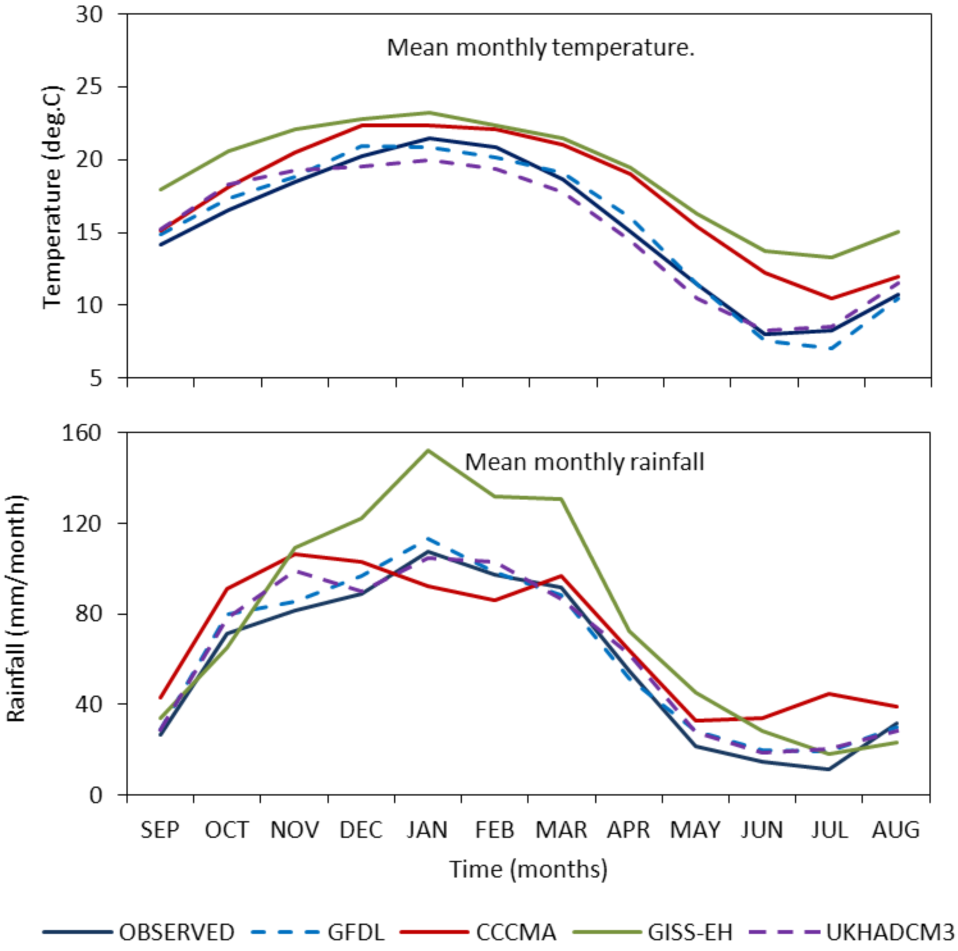

Figure 8:Comparison of model performance with 1980-2008 mean monthly temperature and rainfall.

The differences between the simulated precipitation and temperature and the observed data are shown in Fig. 9. Overall, the data from the GFDL and UKHADCM3 captures the monthly rainfall and temperature totals over much of the region fairly well. The validation statistics are shown in table 9.

Table 9: Statistics between monthly observed and simulated climate for calibration.

	Temperature					Rainfall				
MODEL	STDV	RMSE	Slope	Intercept	R^2	STDV	RMSE	Slope	Intercept	R^2
GFDL	3.2	0.3	1.04	0.61	0.99	35.2	0.5	0.98	4.35	0.99
CCCMA	5.1	2.1	0.06	3.06	0.87	29.2	3.9	0.76	25.15	0.86
GISS-EH	4.5	1.1	0.75	4.52	0.88	65.9	8.7	1.73	-11.64	0.75
UKHADCM3	3.7	0.1	0.91	1.30	0.95	35.2	0.9	0.97	5.54	0.97

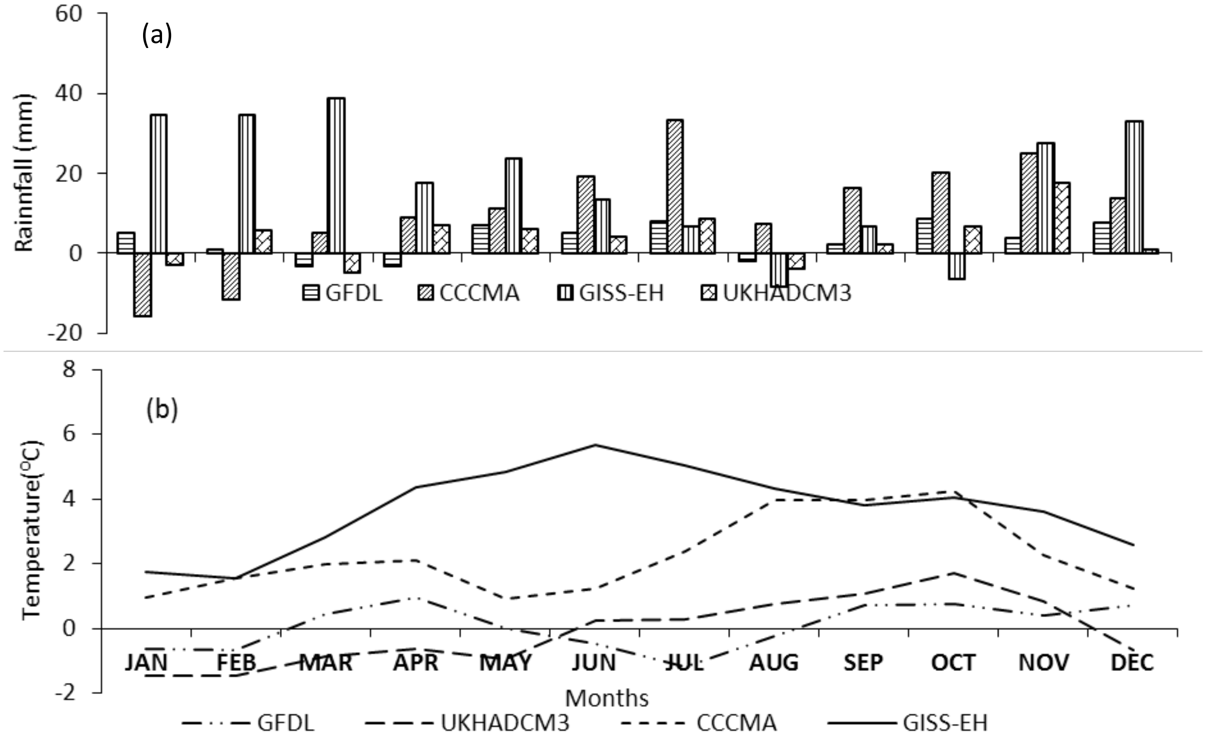

Figure 9: Bias values for the mean monthly (a) rainfall and (b) temperature for study area for calibration for the period of 1980-2008.

Since the selected area is small with less spatial variations, root mean square errors for temperature among the different models are relatively within the accepted range (0.140-2.10). For rainfall, there is a considerable spread in the pattern of correlation among different models and RMSE, which could be related to the influence of the dynamical and topographical characteristics of the region. However, both the pattern correlations and RMSE values are used to select a set of models.

5.2: Effects of climate change

According to Boko et al., (2007), effects of climate change on crop yields will generally be through variations in temperature, precipitation, and other factors like variations in length of growing seasons, increase in crop pests and diseases and alterations of soil fertility, for example through salination. As discussed in sub-sections below, there is uncertainty in magnitude of climate change and its spatial and temporal distribution is still uncertain. For these reasons, GCMs results listed below must be considered as representative of physically plausible future climates, rather than exact predictions.

5.2.1: Temperature Projections

The temperature scenarios that are estimated by GFDL and UKHADCM3 models indicate an increase in temperature for most of the months up to year 2100 (figure10) for both A2 and B2 emissions scenarios. The least warming is estimated for February during which B2 (2050) and B2 (2100) GFDL show an increase of 0.4°C and 0.8°C respectively. The rest of the models also show the same trend. For both 2050 and 2100, temperature increases occur primarily in winter months (May, June and July), with temperature increases of about 50% greater than other month increases. Over the 1980-2008 monthly mean temperature, the highest warming for 2050 is estimated for June for which one of the GCM models, the GISS-EH, shows an increase of 3.8°C and 3.3°C for both A2 and B2 respectively. For 2100 the increase is as high as, 6.7°C, 5.4°C for both A2 and B2 respectively.

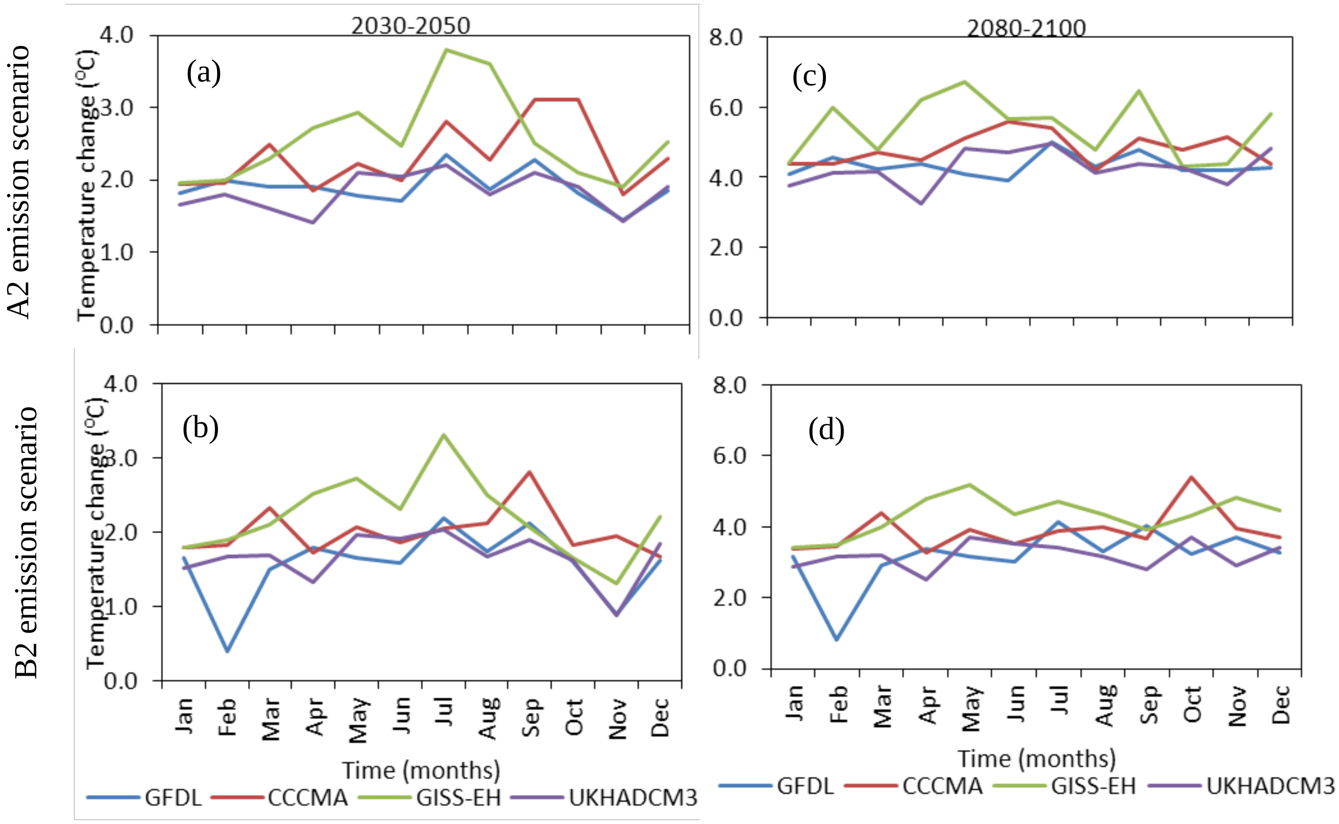

Figure 10: The projected monthly changes in temperature for four GCMs for A2 GHG emissions scenario for the time period relative to 1980-2008 (a) 2030-2050, (c) 2080-2100 and also for B2 GHG emissions scenario (b) 2030-2050 and (d) 2080-2100.

In terms of seasonality, all the outputs from models suggest that there are likely to be more higher temperature events in all seasons. As shown on figure 11, the highest increases in temperature are observed for CCCMA and GISS-EH for medium-term and long-term. Increases of 5.8°C for winter, 5.5°C for autumn, 4.9°C spring and 4.4°C for summer were observed by year 2100 under A2. Increases as high as 3.3°C for winter, 3.2°C for spring and 2.4°C for autumn, and 2.2°C for summer, year 2050 were also observed under B2 scenario. The lowest being the 1.4°C estimated using the GFDL for summer in year 2050 under B2 scenario.

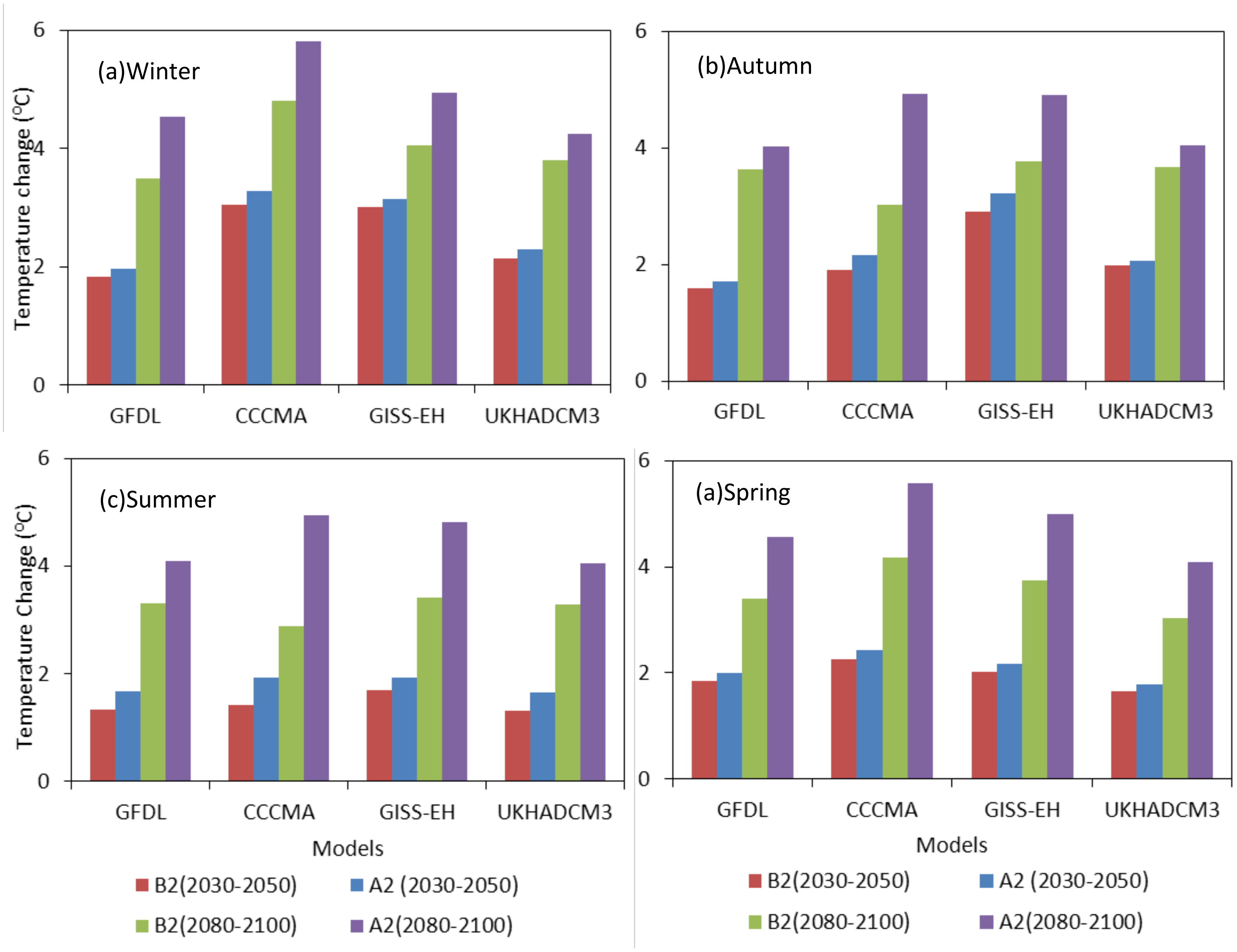

Figure 11: Seasonal average predictions for the emission scenarios A2 and B2 over the whole of Lowlands of Lesotho for 2050, and 2100.

5.2.2: Precipitation Projections

In contrast to modeled air temperature, there is greater spread of variance among the GCMs for precipitation changes. These inconsistencies are explained partly by the inability of GCMs to reproduce the mechanisms responsible for precipitation including, for example, the hydrological cycle (Lebel et al., 2000), or to account for orography (Hudson and Jones, 2002). This, pattern of variable precipitation patterns, along with pattern of warming throughout the 21st century is less consistent with climate projections for mountain areas in Africa (Christensen et al., 2007). The monthly precipitation scenarios that are estimated indicate a reduction in precipitation for most of the models, with the highest decrease of 47 % and 40.6% at the year 2100 for both A2 and B2 respectively depicted by the GFDL and GISS-EH respectively. In spring months (August, September and October) the reduction of precipitation is even worse. The increase in precipitation occurs in the most of autumn months (February, March and April) and winter months, where all models estimate a range of increase of 0.9%-29% and 0.85%-26.5% for both

A2 and B2 respectively in the year 2050. The range of increase for 2100 is 2-47% and 1.6-41% for both A2 and B2 respectively. The increase in July is followed by strong declines in precipitation during august and September and slight increase in October. This is difficult to explain why. It may be consistent to suppose that drought intensity and frequency in summer will increase accordingly.

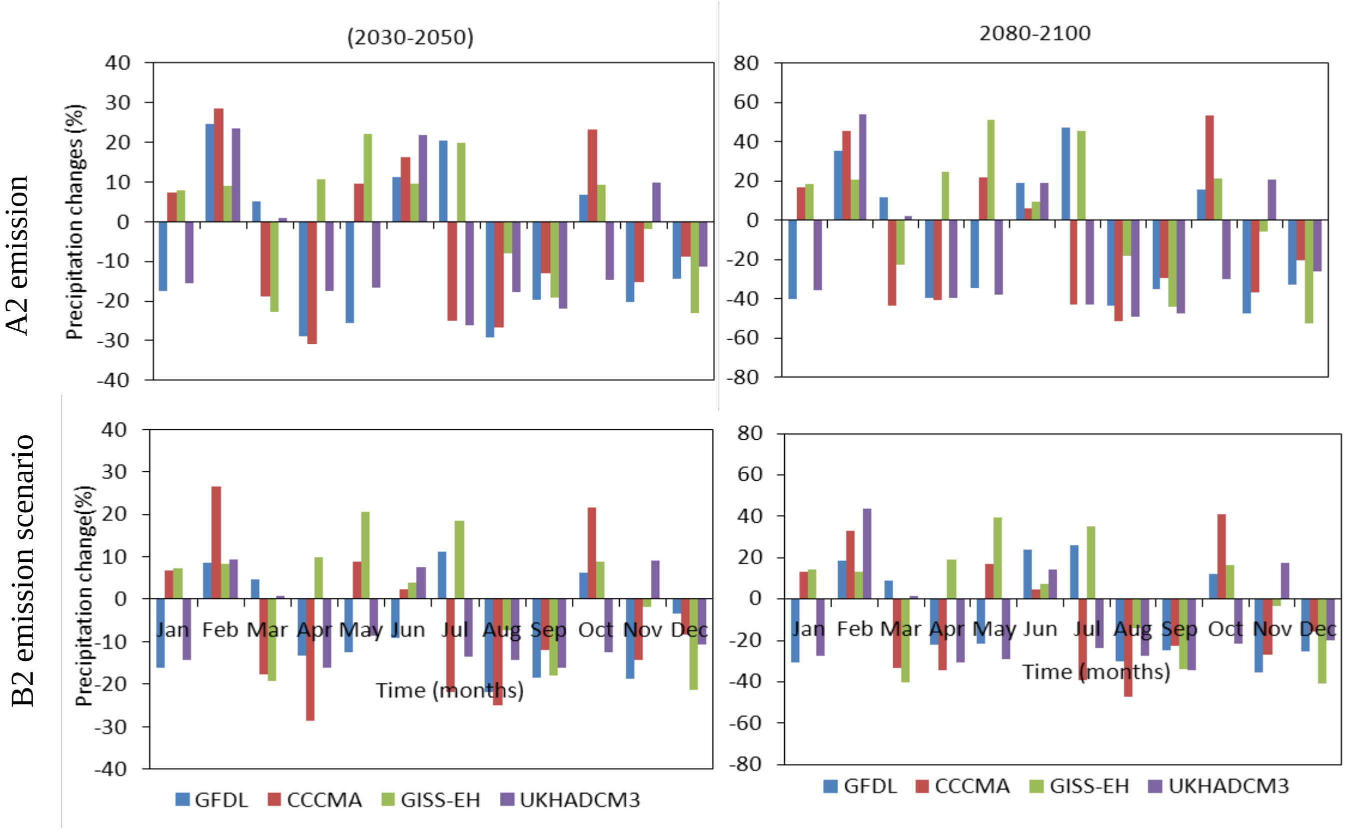

Figure 12: Estimated changes in monthly precipitation for Lowlands of Lesotho in 2030- 2050 and 2080-2100 (relative to 1980-2008) using the A2 and B2 emissions scenario.

Seasonal climate scenarios were created to assess the likely impacts of climate change on seasonal rains, as well as the possible shift in seasonality that could result from anticipated temperature changes. All the models show a decrease in precipitation in summer, for the years up to 2050, and 2100 for all emissions scenarios used in the study. For autumn, UKHADCM3 and GFDL show a decrease in precipitation with the highest decrease being -23% in 2100 under A2 scenario. On the other hand GISS-EH and UKHADCM3 show an increase with the highest increase of 15% in 2100 under A2. In winter, all models indicate increase except CCCMA model. The highest increase in winter; may be due to the increase in May and July being high enough to more than compensate the precipitation decreases in June.

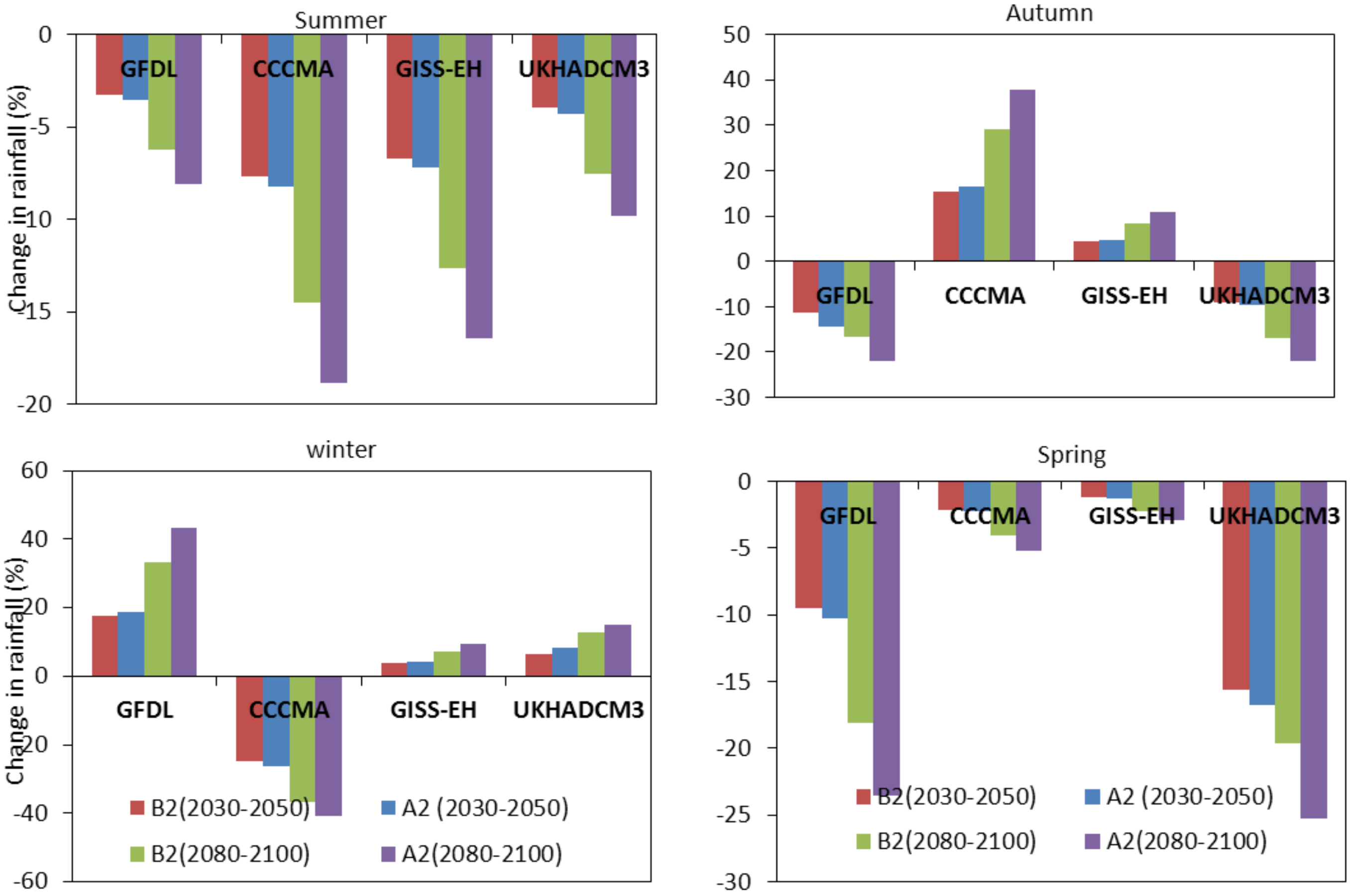

Figure 13: Estimated changes in seasonal precipitation for Lowlands of Lesotho in 2050 and 2100 (relative to 2008) using the A2 and B2 emissions scenario.

The implications of these scenarios are that the study area is likely to experience a warmer climate with lower rainfall in the spring and summer seasons, a higher precipitation in winter, and a gradually increasing precipitation in autumn. The result could be a shift in precipitation patterns in such a way that good seasonal rains that characterize the summer season could then set in late in autumn (LMS, 2000). This is likely to have serious implications for agro-ecological conditions in the country as the growing season is pushed forward and perhaps shortened. The increased temperature and decreased precipitation during growing season may lead to early or late flowering, reduced quality and quantity of desirable plant parts, and increased mortality. The conditions of water stress will make crops more vulnerable to attack from insects and disease organisms. On the other hand, an increase in precipitation in winter may suggest increased activity in frontal weather systems which may result in heavier snowfall occurrences and strong distressing winds which often bring disasters and human suffering. If not in the form of snow, it is also likely that the increased precipitation may mean increased severe storms and floods, particularly in winter, a potential for the further impoverishment of the soil. This is disadvantageous for the common farmers practice for winter wheat. The reduction in mean seasonal precipitation under climate change conditions also implies that water availability for irrigation purposes would also be affected accordingly. This will reduce the effectiveness of irrigation as a strategy to combat climate change (Matarira, et al., 1995). All these conditions have a potential to adversely affect the future performance of the already vulnerable agriculture unless bold adaptation strategies are developed and adopted.

5.2.3: Models performance in comparison with other climate studies.

Results obtained in this study thus prove to be in agreement with previous studies. The climate model tends to be doing fairly well since the obtained results are within range proposed by IPCC AR4. According to IPCC AR4 the likely range for temperature increase by 2100 for African countries is as follows:

- A2= 2.0°C-5.4°C and the best estimate is 3.4°C
- B2= 1.4°C-3.6°C and the best estimate is 2.4°C

Hernes et al. (1995) and Ringius et al.(1996) constructed climate change scenarios for the African continent that showed land areas over the Sahara and semi-arid parts of southern Africa warming by the 2050s by as much as 1.6°C. For southern Africa, Hudson and Jones (2002), using the HadRM3H RCM with the A2 emissions scenario, found for the 2080s a 3.7°C increase in summer (December to February) mean surface air temperature and a 4°C increase in winter (June to August).

And for rainfall, Using RCMs, Tadross et al. (2005b), found a decrease in early summer (October to December) rainfall and an increase in late summer (January to March) rainfall over southern Africa. In addition to this, Verdin (2005) has identified steep decline in rainfall in the first part of the growing season for Ethiopia in the past 10 years. Joubert & Hewitson (1997) nevertheless conclude that, in general, precipitation is simulated to increase over much of the African continent by the year 2050.

5.3 CROPWAT estimation

The model was evaluated with respect to its ability to replicate the mean and standard deviation (SD) of observed yields for the whole region and per district. Simulated mean yields are significantly larger than statistical mean yields (one-tailed t test, $P<0.05$), shown by a value of Root Mean Square Error = 0.074 mt·ha−1. The likely causes of this overestimation is that the crop model is not sensitive to many environmental stresses such as cold temperatures, drought, flooding, pest, harvest lost, which have been reported by Chipanshi et al. 1999; Jagtap and Jones 2002. It is obvious that the model tended overestimate reported census yields. Despite the encountered overestimation, simulated mean yields and observed yields were correlated ($R^2 = 0.71$) for the whole region ($P<0.05$ Pearson correlation analyses). Closeness between observed and simulated yields is important when making long-term decisions.

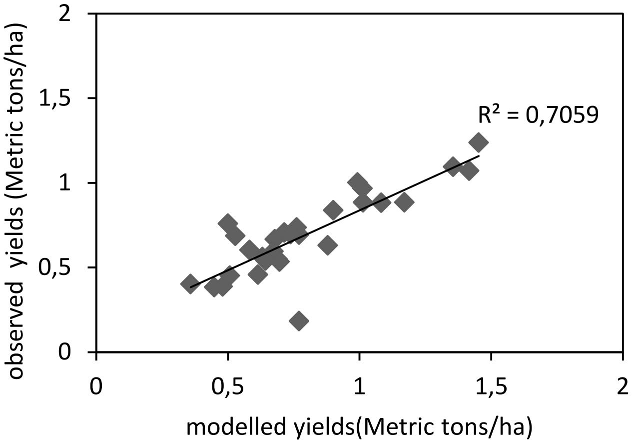

Figure 14: Comparison of yields between measured and modeled yields for three stations from 1980-2008.

Looking at district level the model has slightly overestimated the crop yields values by 0.6% Maseru. Despite this slight overestimation, the model has accurately reproduced the crop yields. This was noticed especially when considering the crop yield values obtained from direct measurements. In Leribe the mean of observed yield was 0.3% lower than the simulated yields. Whereas in Mohales'Hoek the mean of observed yields was 1.5 % lower than the simulated yields. These differences may be due to the error of field experiment data and weather data. Overall results show that CROPWAT model is an adequate tool to simulate crop yields, particularly to evaluate relative changes in crop yield in relation to climate change

Table 10: statistics between observed and simulated crop yields for calibration.

Crop	Statistics	Leribe	Maseru	Mohales'Hoek
Maize	slope	0.73	0.73	0.97
	intercept	0.22	0.19	0.09
	R^2	0.68	0.62	0.8
Wheat	slope	1.27	1.05	0.88
	intercept	-0.21	-0.04	0.13
	R^2	0.71	0.81	0.64
Sorghum	slope	0.95	1.21	0.86
	intercept	0.06	-0.09	0.09
	R^2	0.63	0.65	0.51

5.4: Crop yields responses to climate change

In 1980-2008, the maximum total maize, wheat and sorghum yields were 4.55, 4.09, and 3.632mtha^{-1} respectively for Leribe, for Maseru they were 1.452, 1.182 and 2.238mt ha^{1} respectively and Mohales'Hoek 1.813, 3.797, 1.22 mtha^{-1} respectively. The cultivated area for maize, wheat and sorghum were 31,056 ha, 1,577ha, and 5,767ha 22 million ha in Leribe, in Maseru, 25,263ha, 3,250ha, and 7,241ha and for Mohales'Hoek, 14,525ha, 3,262ha and 8, 792ha respectively. Assuming the same cultivation area, the same cultivar yields as present, and no nutrient stress. All projected climate change scenarios without CO_2 fertilization effect show a general tendency towards diminishing future crop yields in all agricultural regions. As it can been seen from the results presented below, the decrease in yields is highest for GISS-EH and CCCMA as opposed to the most applicable models for assessment GFDL and UKHADCM3 in the year 2050 and 2100 for both A2 and B2.

5.4.1: Key findings

Maize

Figure 15 shows the potential impacts of the projected climate change on maize yields of studies sites. For all time periods, rainfed maize production is predicted to decrease under both A2 and B2 scenarios by GFDL and UKHADCM3. Taking the mean over all regions, yields reductions oscillate between -6.5 and -17.4% for GFDL and between −7.5 and -17.6% for the UKHADCM3 model by the year 2050 for A2 scenario. But for B2 (2050) the yields vary between -3.8% and -13.75% for both GFDL and UKHADCM3. By 2100, maize showed the most negative effects under GFDL and UKHADCM3, with a 30% and 19% yield decrease contrasting to present for the A2 and B2 respectively.

At district level, Maseru which is the capital city of Lesotho, there is strong likelihood that climate change will make the region a non-maize producing area (fig.15(c), (d)). If this becomes real, the whole capital city, will not adequately supply its population with staple food crop. The projected climate change shows also that Mohales'Hoek has a marked potential reduction in maize yields over the baseline scenario. As it can be seen on figure 15, maize yield is predicted to decline by 12.7%-27.5% and 10. %-21.1% compared to baseline for A2 and B2 respectively for this district. Expanding the intensive maize production to those areas might be a good adaptation option to future climate change. These results for Maseru and Mohales'Hoek also reveal that the yield changes depend on water availability. Maseru and Mohales'Hoek are projected to see drastic increasing water stress in the maize crop since the highest values of ETo are simulated in these districts. For Mohales'Hoek, the highest projected ETo values by GISS-EH are 580mm and 690mm for 2050 and 2100 under A2 scenario (see appendix C) as estimated. For Maseru, the highest ETo of 503mm and 599 mm were observed for 2050 and 2100 respectively under A2. Apart from this, Mohales'Hoek is in fact located in the central southern part of the country and characterized by high diurnal temperature during rainy season (LMS, 2000).

As for Leribe district where the annual average rainfall is 1200 mm/year (Maseru and Mohales'Hoek≈800mm/year) and where cropping systems are most intensive with higher inputs of fertilizers (LSM, 2000), climate change will also likely offsets yields, but with insignificant impact as compared to other districts. If the proper timing of planting dates is maximized, negative impacts may probably not be encountered. For all time periods, rainfed maize yield is predicted to decrease under both A2 and B2 scenarios, causing 1-12% and 1-11.5% lower yields compared to the baseline for A2 and B2 respectively. The decrease is higher under A2 2100 giving decrease of 12.13% and the lowest in 2050 under B2.

Given that maize is a crop which does not need a lot of water, the implication of these results will be that drastic temperature increase is a threat to maize plantation. Temperature can affect the crop at different stages of its growth starting from germination, to vegetative growth and then to reproductive growth (Ramadoss *et al.*, 2004). Wheeler (2000) observed that short episodes of high temperature at critical stages of crop development can impact yield independently of any substantial changes in mean temperature. Another study done by Stewart (1997) indicated that during vegetative growth, maize has a maximum response to temperature of between 25 - 30°C and during reproductive growth, maize responds well to temperatures above 12°C.

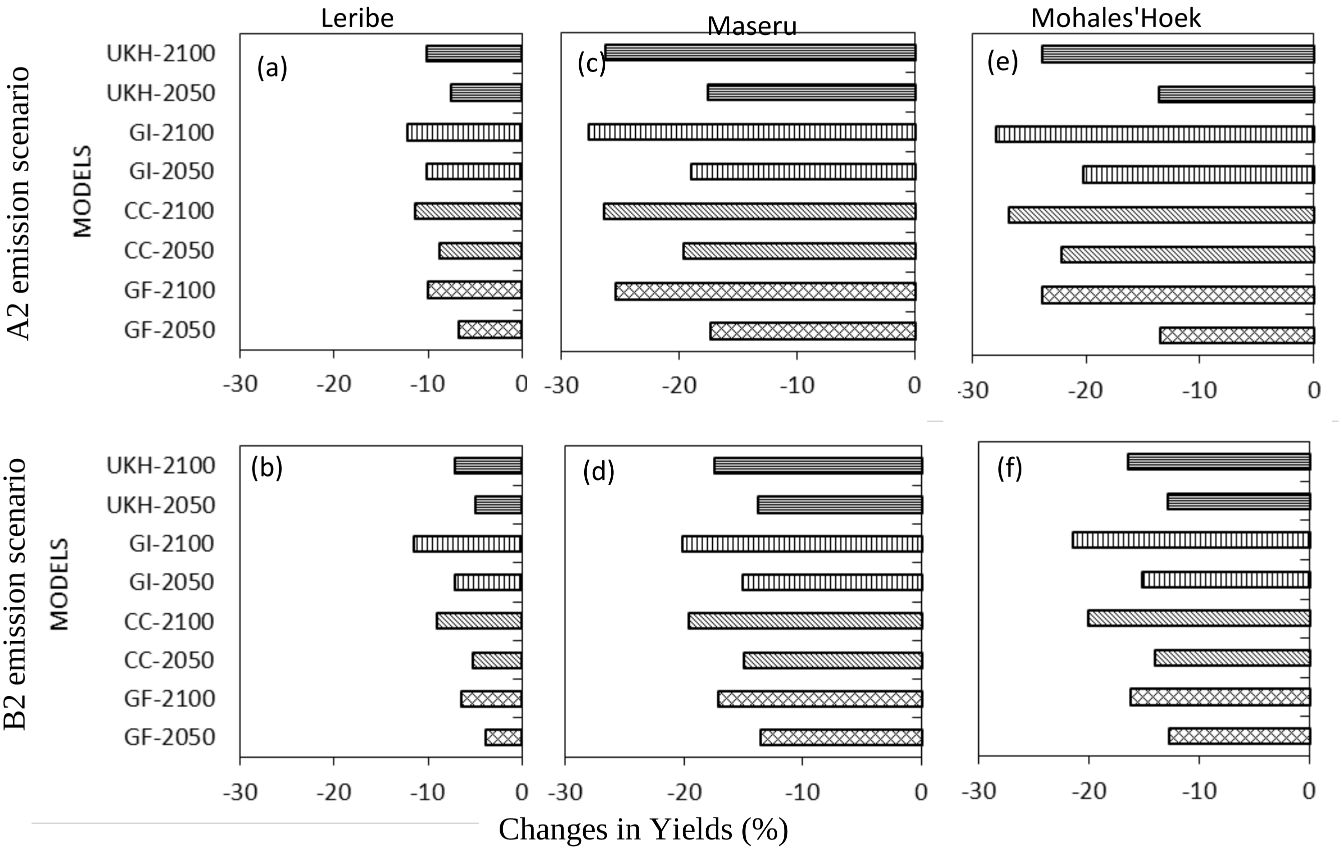

Figure 15: Projected changes in maximum maize yield (%) under baseline (1980-2008) sorted by climate change scenarios and time period. (a) & (b) for Leribe, (c) & (d) for Maseru, (e) & (f) for Mohales'Hoek for A2 and B2 scenarios respectively.

- **Winter Wheat**

Eventhough precipitation is projected to increase in winter, the wheat turned not to respond positively. Without the CO_2 direct effect and keeping the same sowing date and wheat varieties as today, the average yields of rainfed wheat showed the tendency to fall for all districts for both A2 and B2 emissions scenarios (see figure 16), probably because the higher temperature may shorten the growth period and increased precipitation in winter. A substantial decrease in wheat yields is generally estimated by 2100 compared with current yields for the A2 and B2 emissions scenarios. Wheat yields across all locations varied between 10.9 and 22.8% for GISS-EH and CCCMA. With close consideration to GFDL and UKHADCM3, yields decrease fluctuate between -7.8% and -8.6% for A2 in the year 2050. For B2 in 2050, they fluctuate between-6.5%

and -7.5%. By 2100 the same models (GFDL and UKHADCM3) depict the decrease between 11.3-12.7% and 10-12.4% for A2 and B2 respectively.

The conclusion can be deduced from the fig. 16 that in the Maseru district the rainfed wheat yield will decrease more in A2 scenario as compared to other districts. The same applies for B2 scenario but the decrease is more in A2 scenario than in B2 scenario. The possible explanation for this behaviour is as follows: Southworth (2000) and Jones & Thornton, (2003) found out that wheat yield decreases is greatest if higher temperatures occur during the period when the wheat ears are swelling since they speed up plant's development so that it matures sooner. And indeed the future temperature projections showed that the increase of temperature will be highest in winter. Furthermore, Hoogenboom, (2000) showed that winter wheat is more sensitive to soil temperature. It affects planting and germination and flowering. Eventhough air temperature is projected to increase, this may not necessary imply an increase in soil temperature, the reason being (although not captured by the models) that increased precipitation in winter is anticipated to be in snow form. Accumulation of snow affects aeration of the soil and depresses microbial activity of soil microbes. This implies less nutrient availability. The Projected warmer and wetter conditions in winter also affect the prevalence of pests, diseases and weeds (not included in this yield model).

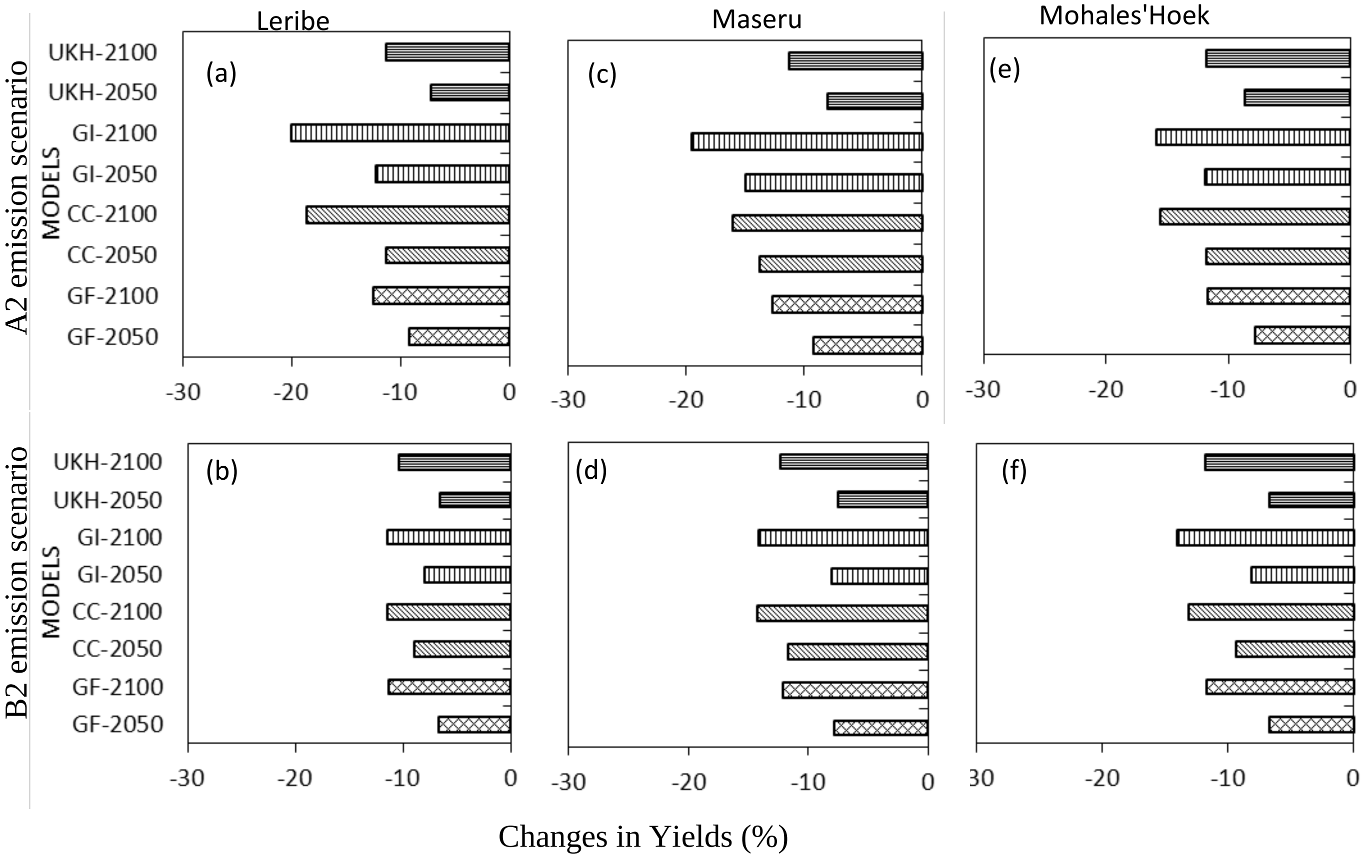

Figure 16: Projected changes in maximum wheat yield (%) from baseline (1980-2008) sorted by climate change scenarios and time period. (a) & (b) for Leribe, (c) & (d) for Maseru, (e) & (f) for Mohales'Hoek for A2 and B2 scenarios respectively.

- **Sorghum**

The sorghum results appear to indicate that under future scenarios, the impact on yields will be negative, without considering the effect of CO_2. GFDL and UKHADCM3 show that in all the districts mean reductions of 9.8% and 6.5% under A2 emission scenario is attained for year 2050 and 2100 respectively. For B2 UKHADCM3 and GFDL simulations show mean reduction of 2.5% and 6.8% for year 2050 and 2100 respectively. The greater impact of SRES A2 can be attributed to the stronger increase in temperature projected with this scenario during the growing season of sorghum, close to 5.7°C in maximum temperatures and 3°C in the minimum ones, overriding the highest increase of by 3.8°C projections under SRES B2 2100.

The decreases vary according to the agricultural district investigated. The range for decrease in Mohales'Hoek 4.3-14.8% and 1.2-11.6% for both A2 and B2 in the year 2100 this range is small as compared to Maize. There is evidence from WFP, (2010) that in this region, farmers are starting to switch from maize to sorghum. However, the slight decrease in sorghum production cannot yet compensate for the substantial projected fall in maize yields. This finding is interesting since it revealed high stress-tolerance ability of sorghum as the highest ETo of 690mm was observed in this region. For Maseru the range of decrease 8.5–14.8% and 3.6–14.4% lower yields compared to the baseline for A2 and B2 respectively. Only the area of Leribe that has favorable meteorological and edaphic condition represents slight decrease with the range of 4-14.2% and 3.6-11.7% for both A2 and B2 respectively in the year 2100.

To support the finding, (Carbone et al., 2003) found out that sorghum development is sensitive to the rise in temperature; its growth is affected greatly by temperature elevation and precipitation variation. Boote and Sinclair, (2006) found out that sorghum does well under moderately cool and somewhat optimum daylength conditions, allowing the crop to progress slowly through the season (but to finish before frost), so as to maximise time for assimilating capture and time for assimilating partitioning to reproductive structures. From the result one can conclude that, the projected increases in summer (which is the growing season for sorghum) temperature will hinder these conditions found by Boote and Sinclair, (2006). There will be acceleration in maturation of sorghum.

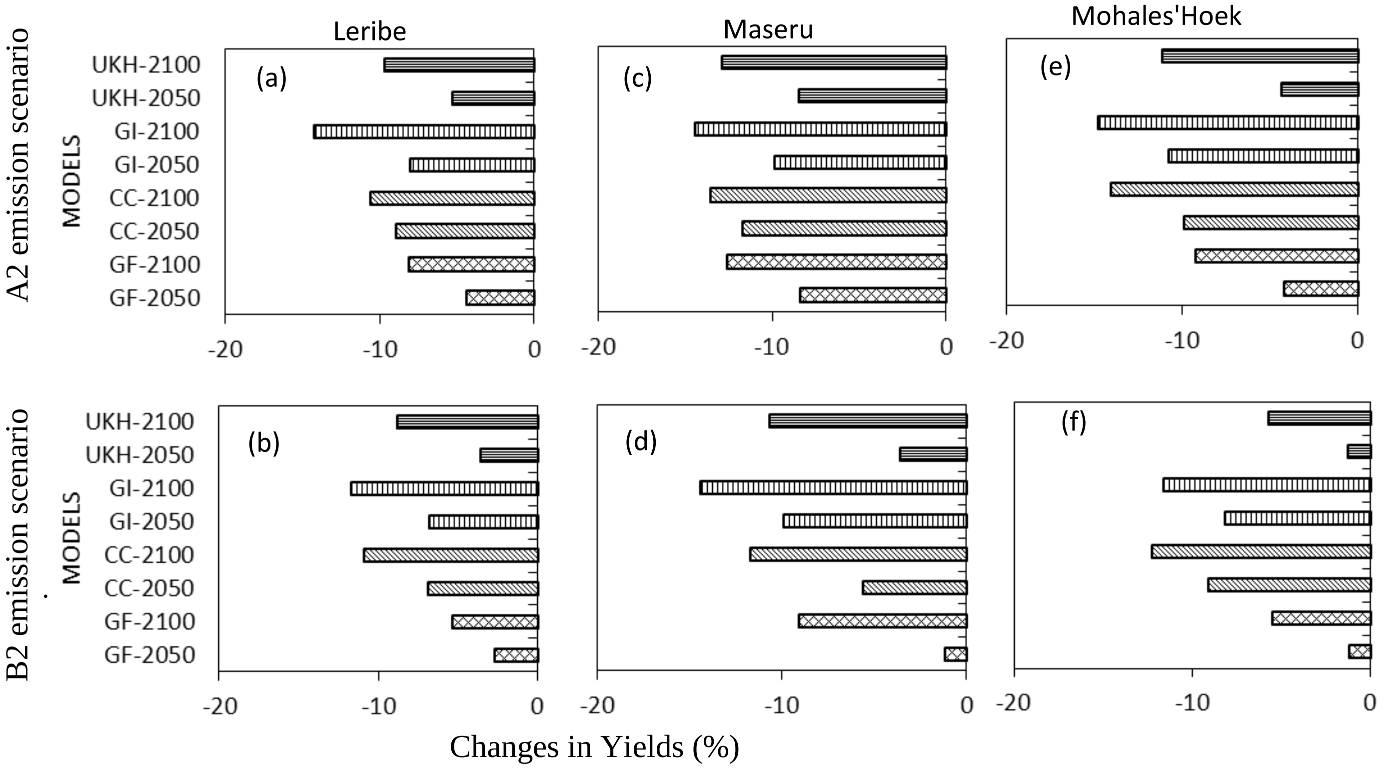

Figure 17: Projected changes in maximum sorghum yield (%) under baseline (1980-2008) sorted by climate change scenarios and time period. (a) & (b) for Leribe, (c) & (d) for Maseru, (e) & (f) for Mohales'Hoek for A2 and B2 scenarios respectively.

5.5 Irrigation requirements

Changes in crop water demand did not vary much between the districts so the presented values are average of three districts. However it did depending on the emission scenario, decade and crop. In the 2050s and 2100s, as expected the irrigation demands for winter seem to be low due to projected increases in winter precipitation. Irrigation requirements at first were found to be lower in the near-term than in the future. However this observation is inconclusive since the precipitation intensities have not been taken into consideration. Winter precipitation intensities have been shown to increase in the future (fig.13); this indicates a high probability of less infiltration occurring, and more runoff. It is also possible to see how irrigation demands of maize and sorghum are high as compared to wheat. There are possible explanations to this distinct behavoiur. One could be sorghum and maize are grown in months that the rainfall highest decrease is projected to be 14% and 11 % by 2050 and 29% and 21% by 2100 for both A2 and B2 respectively for UKHADCM3. As for GFDL, the highest rainfall decrease is projected to be 20% and 15 % by 2050 and 39% and 30% by 2100 for both A2 and B2 respectively. Apart from rainfall decreases warmer temperatures are expected, and irrigation needs could rise because of the higher evaporative demand as a consequence of higher temperatures. Probably if CO_2 effects were considered, irrigation requirements could decrease as a result of the enhanced water use efficiency under CO_2-enriched environments (Kimball *et al.*, 2002).

Overall irrigation demand is higher for GISS-EH and CCCMA scenarios as compared to UKHADCM3 and GFDL scenarios.

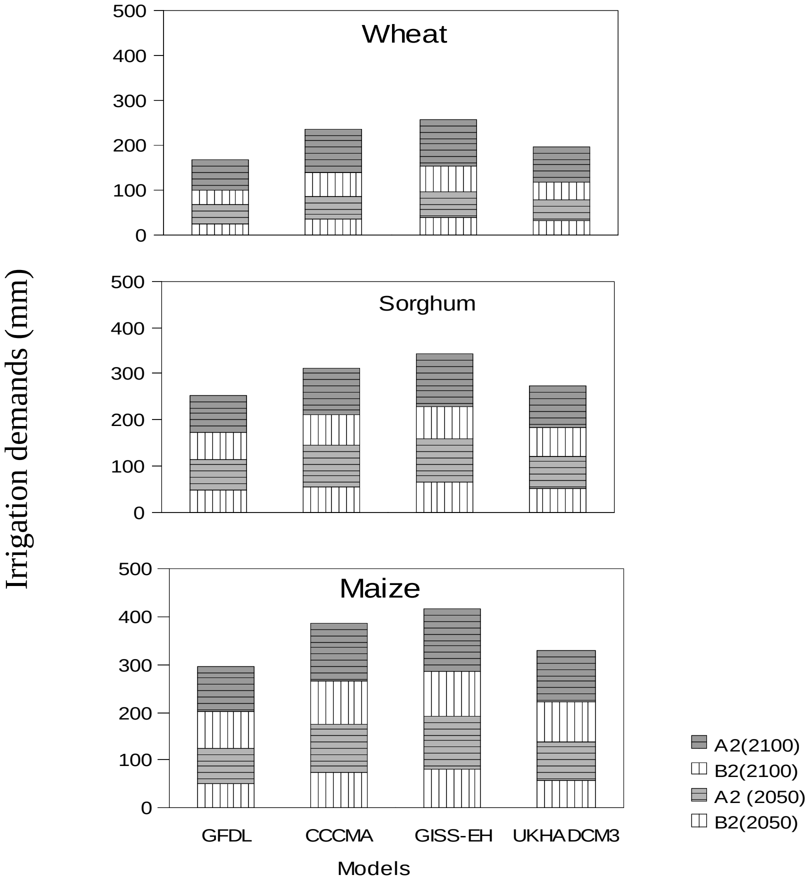

Figure 18: Average estimated irrigation demand for different crop under climate change.

5.6: Models performance in comparison with other climate-crop yields studies

From the studies done, different results have been obtained by different researchers depending on how climate has been and is expected to affect maize, wheat and sorghum production in different parts of the world both at regional and local level situations.

- In IRIN 2010 reported, in year 2009 maize yields were even less than in 2007 in Lesotho.
- In Burkina Faso, Wang (2008) reported a decrease of 23% and 8% in sorghum and maize yields respectively.
- In six districts of Kenya, a study done by Karanja (2006), showed a 40% reduction in maize yields and 31% in wheat, following an increase in temperature by 4°C and 20% rainfall reduction.
- A study by Jones and Thornton (2003) in Africa and Latin America showed both an increase and reduction in maize yield in different parts of the study areas with a reduction

of about 10% in total production in both regions to 2055 due to the expected increase in temperature and less conduciveness of rainfall to maize production. Another study done in 2002 in Africa showed a substantial spatial shift in maize cultivation in the region due to climate change by 2055.

- In Zimbabwe, Matarira *et al* (1995) reported that maize production at all the stations where research was done is more consistent under normal climate than under climate change conditions. Thus, they said that climate change introduces greater variability in maize yields in Zimbabwe.

5.7: Summary of results

5.7.1: Climate change

- The MAGICC/SCENGEN outputs for the two future time slices chosen show that some seasons will experience precipitation reductions while others will experience increases. However, this extra rainfall was insufficient to offset the impact of temperature increases on crop yields, since warmer conditions also enhance water demand. Monthly and seasonal temperatures are projected to increase by as much as 3°C to 5°C towards the end of 21st century. These increases are greater under SRES A2 as compared to B2.
- Precipitation available per growing season will be reduced by more than 20% due to climate change at all districts. The greatest reduction in available precipitation will encountered when the cereals are planted early rather than late.
- The reduction in mean seasonal precipitation under climate change conditions implies that the water available for irrigation purposes will reduce the effectiveness of irrigation as a strategy to combat the effects of climate change.

5.7.2: Projected Crop Yields

- Observed annual rainfall, temperature and annual crop yields were weakly correlated for one district on which the analysis was carried out, indicating that rainfall and temperature are not the sole effects behind crops activities. The current change may rather be believed to have been caused by a combination of driving forces like amount of applied fertilizers.
- The good agreement of the simulated yield and in situ observation indicates that CROPWAT model can be used to project the impacts of climate change on Lesotho's cereal crops.
- The simulated crop evapotranspiration decreases in most areas despite the large increases in temperature and potential evapotranspiration. This is due to the shorter growing season, which reduces the total amount of evapotranspiration and the decreased demand of moisture by the crop, since it is not growing at the full capacity (see Appendix C). The amount of irrigation water will generally decrease for the same reasons
- Climate change will have negative impacts on crops yields. To summarize, climate change is unlikely to benefit Lowlands of Lesotho maize production as the potential maize yields may decrease in key maize planting areas, if the present agronomic practices are not adapted to the changing climate. The analysis suggested that yields would decrease will be highest for two out of three study sites (Maseru and Mohales'Hoek).
- From the above analysis, what also emerges is that the projected climate change conditions, with warmer temperatures and lower precipitation, are likely to have a slight

negative impact sorghum yields leading to possibilities for reduced imports in the case of maize, and higher exports in the case of sorghum.

- The decrease in wheat crop yields like other crops, in the future period is mainly due to increase in temperatures during the growing periods.

On the whole, the simulated changes in crop yields are driven by climate change. The yield decreases are caused primarily by the increase in temperature, which shortens the duration of the crop growth stages particularly the grain fill period. The season length is greatly reduced under these scenarios.

6: ADAPTATION OPTIONS

From the results of this study, it has been shown that climate change is introducing another dimension to the unreliability of weather patterns in Lesotho. It is likely responsible for the increase in the frequency of both periodic droughts and crop failures that have been observed in recent years (LSM, 2000). Given such recognitions, McCarthy et al., (2007) encourages adaptive measures at both national and local level that can be taken as a reactive approach to combat climate change impacts to ensure that the nation is food secure. However, Smith and Skinner, (2002) observed that these reactive approaches may prove to be costly to produce satisfactory results hence the following determinants were taken into consideration when stating the suggested adaptive measures.

6.1: Determinants of adaptive capacity

Adaptive capacity is defined as 'the general ability of institutions, systems and individuals to adjust to potential damages, to take advantage of opportunities and to cope with the consequences' (Boko et al., 2007). According to McCarthy et al., (2007), economic resources (expressed as economic assets, capital resources, financial means, wealth or poverty), technology, information and skills, infrastructure, institutions and equity are the key determinants.

- **Economic Resources**: Generally, adaptive capacity is higher with increase in economic resources and lower with reduced economic resources (Bhadwal, 2006). Thus, developing countries deserve measures that are not costly due to low economic resources to invest and to offset the costs of adaptation.
- **Technology:** adaptive agricultural technologies are important since the potential adaptation options reduce without technology.
- **Information and Skills**: Adaptive capacity reduces without informed, skilled and trained personnel. In general, countries with more 'human capital' or knowledge have greater adaptive capacity (McCarthy et al., 2007).
- **Equity**: Equitable access of resources is also important since it implies adaptive capacity is likely to be greater (WHO, 2007). Thus, both availability and entitlement to resources are important (Bhadwal, 2006).

However, Lesotho like other African countries generally has low adaptive capacity due to lack of economic resources and technology and high vulnerability as a result of depending much on rainfall (Bhadwal, 2006), though the capacity varies for different systems, sectors and it is location specific (Yohe and Tol, 2001). Based on this fact and the results obtained, for the agricultural sector, adaptations to climate change can occur at two levels:

1. Farm level
2. Governmental level

6.2: Farm level

In response to projected drier spring and summers conditions that will be introduced by climate change, there is a likelihood that farmers will be forced to adopt drought resistance species (Toit et al, 2000) yet the shorter growing season is likely to turn their attention to those species which have faster maturity. Apart from crop diversification, amongst other strategies of improving adaptation in Agriculture includes the promotion of irrigation development, soil liming and crop intensification, including mixed and double cropping (World Bank, 2006). To adapt to shift in growing season, farmers can shift the planting dates.

6.2.1: Crop diversification

Switching from monocultures to more diversified agricultural production systems will help farmers to cope with changing climatic conditions. Monocultures are more vulnerable to climate change, pests, and diseases. Ministry of Natural resources (2000) provides evidence about Asparagus adoption in Lesotho. The crop bears many advantages, suitability to Lesotho's climatic conditions and soils, limited proneness to pest and diseases. For crop diversification to be effective, introduced foreign crops should demand less establishment costs, and less management demand.

Apart from this, with ongoing increasing ambient CO_2 concentration (not considered in this study) and a warmer climate, especially in winter as results suggest, new crop varieties with high yield, warm-winter resistance under should be favoured for adaptation in a future climate change. Cross breeding of cereal varieties is considered ideal for enhancing morphological characteristics. This aims to overcome the impact of soil and climate on yield, as well as environment change, to keep yield at a high level. It is also significant for acclimation to CO_2 fertilization effect (Erda, et al 2005). For example Tingem (2009), found out that in Cameroon the use of later maturing new cultivars proved to be extremely effective in offsetting adverse impacts. Under climate change scenario GISS A2 2080, a 14.6% reduction in maize yield was converted to a 32.1% increase; a 39.9% decrease in sorghum yield was converted to a 17.6% increase.

6.2.2: Crop intensification

In addition to introducing exotic crops, the sector can also focus more on expanding the cultivated area for crops which are locally-produced, but for which their domestic demand is largely satisfied from imports. These include crops like potatoes, grapes, onions. LVAC (2007) observed that many of these crops demonstrated higher labour intake and better farmer returns than dryland crops. For this to be effective will require removal of subsidies on crops that do not perform well in harsh climatic conditions (Smith and Skinner, 2002). The government should provide credit facilities to farmers so that they can buy seed varieties and fertilizer.

6.2.3: Planting dates

Changing sowing dates may be effective in counteracting adverse climatic effects because of the narrow rainfall band that strictly determines the timing of farm operations in Lesotho. Adjusting crop planting time could avoid light energy loss while adjusting the planting area and region of C3[10] and C4[11] crops (Sage, 2007) and increasing plant density could increase the accumulation

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[10] Plants whose carbon-fixation products have three carbon atoms per molecule (Sage, 2007) like wheat.

and efficient use of CO_2. The distinction between C3 and C4 is important due to different stress-tolerance. C3 plants during increased temperatures and water stress do not benefit. This is due to their inability to photosynthesis with closed stomata. C4 plants have mechanisms of surviving in stressed conditions due to their ability to photosynthesis with tightly closed stomata.

6.2.4: Irrigation development

Given that a large part of arable land is under rain-fed farming, the Government and farmers may decide to increase its investment on irrigation, both small-scale and large schemes. This may require the farmers, NGOs and government to invest in research such as water harvesting purpose technologies, and irrigation schemes (Smith, 2008).

6.2.5: Cropping system

Changes in cropping systems can offset many of the potentially negative impacts of climate change (Smith, 2003). The use of conservation tillage, intercropping and crop rotation practices will enhance the long-term sustainability of soils and improve the resilience of crops to changes due to climate change (EPA 1992). Farmers may also consider the use of greenhouses for the production of some of their products.

6.2.6: Restoration of organic soils

This option involves increasing the levels of soil organic matter, of which carbon is the main component. This would translate into better plant nutrient content, increased water retention capacity and better structure, eventually leading to higher yields and greater resilience (FAO, 2009). However, this option involves difficult trade-offs. Restoration of organic soils enables greater sequestration of C in soil, but may reduce the amount of land available for food production (FAO, 2009). Some trade-offs can be managed through measures to increase efficiency or through payment of incentives/compensation (FAO, 2009).

6.3: Government level

The government of Lesotho recognizes agriculture as a key production sector for economic growth, employment, income generation and the achievement of food security. It is for this reason that the government should commit itself to promotion of a growth strategy that capitalises on Lesotho’s comparative advantages, and ensure that growth policies target the poor directly through programmes that address production at the household level. These options concern both NGOs and Government as a whole.

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[11] Plants whose carbon-fixation products have four carbon atoms per molecule (Sage, 2007) such as maize and Sorghum.

6.3.1: Weather and seasonal Forecasting

Non-governmental sectors and governmental sectors should focus more on improving the ability for weather forecasting. Enough funds to the meteorological department for buying equipment which would help capture reliable information, analyse and make reliable forecast should be allocated to make this effective. This is especially true, if droughts could be forecasted so much in advance that farmers could switch to more drought resistant crops and adjust the planted land to expected rainfall and temperature.

6.3.2: Farmers' subsidies

Agriculture is affected in many ways by a wide range of government policies that influence input costs, product pricing and marketing arrangements. Smith (2003), have noted that relatively minor alterations to these policies can have a marked and quite rapid effect on agriculture. Rosenzweig (1993) observed that, there may be social or economic reasons why farmers are reluctant to implement adaptation measures, for example, increased fertilizer application and improved seed stocks may be capital- intensive and/ or not suited to indigenous agricultural strategies. Thus, changes in government policy as a result of climate change or anticipated change would have a very significant influence on how agriculture ultimately responds.

6.3.3: Land policy and infrastructure development

Government policies pertaining to land and water resources, which represent the basic foundation for agricultural production, should be more explicit in having the implementing agencies give due consideration to the possible impacts of climate change (Matarira, 1995). Through its policies on water resources management, and product pricing, government can put both reactive and anticipatory adaptive measures into place (OTA 1993). Government agencies in charge of executing the resettlement program can also take into consideration the anticipated impacts of climate change (Smith, 2003). As more areas become marginal, there will be a shift to more intensive agricultural production in the more favorable areas. Hence, if such areas can be identified, supporting infrastructure can be improved in these areas (Smith, 2003, Matarira, 1995). The setup of such infrastructure may not be critical at this stage; however, it can still be fully utilized and significantly improve agricultural production efficiency in these areas (Parry and Duinker, 1990).

7: CONCLUSION

The main conclusion from the crop-climate modeling is that the estimated effects of climate change as evidenced in the simulated crop yields are indicative of potential problems ahead of Lesotho. The derived results support the current crop yields trend in Lesotho. Without the appropriate policies or adaptive strategies in place, the smallholder farmers will find it extremely difficult to operate sustainable agricultural production systems in an environment with changed climatic conditions. Climate model projections indicate progressively larger changes in the 2050s and beyond depending on the level of future emissions. The average temperature increase in Lowlands of Lesotho by the end of the 21st century may be between 3 ˚C and 6 ˚C. The results of the project further suggest that, for the study area in the medium- term and future terms (2050s to 2100s), the relative abundance of water for agriculture will decline drastically under climate change conditions. A major implication of precipitation projections is that irrigation and drainage technology are likely to become even more important in the coming decades than they are now.

The crop-modeling approach proved to be very useful for evaluating crop water use across a country. Comparing the two Scenarios A2 and B2, different districts have different results. The A2 scenario produces the highest impact of climate change than B2, showing the most negative effects on districts future crop yields. The outputs of the CROPWAT model confirm that in the future and the medium-term (2050s) under A2 and B2 Scenarios, the rainfed maize yields would reduce in all districts. The decrease for the districts located in the northern half of the country is relatively smaller as compared to rest of the districts. As for sorghum and wheat the increase in temperature showed negative impact for all districts under both A2 and B2. Overall, the impact of climate change on district's three main crops yields would have more negative impacts. This high sensitivity of crops shows that they should receive more attention. However, some factors and uncertainties have not been fully included in the analysis, like the effects of pests and diseases, future adaptation strategies, which would also modify the results on crop yields. These analyses are based on four GCMs and two emission scenarios (A2 and B2). Further analysis should reveal whether other climate models and emission scenarios show the same trends.

Since the projected impact on crop yields would be severe, farmers should adapt to the new climatic conditions, and for this purpose several strategies are suggested. Among them, the simplest one could be to advance crop sowings taking advantage of the prolonged frost-free periods. As the shift in growing season is evidenced from the climate change results, it is worth concluding that shift in planting dates is an effective adaptive measure among many suggested measures.

8: FUTURE RESEARCH PRIORITIES

Climate change will result in impacts whose direction, magnitude, timing, and path are neither fully understood nor accurately predictable. Models alone do not provide an answer. There is, thus, a need for sustained integrated research to enable the prediction of the impacts of climate change with more confidence, especially at the regional and national levels.

(a) Cross-disciplinary research
  - Researchers from natural and social sciences need to work together to come up with workable solution for adapting climate variability and changes.
  - Fully integrated crop-climate modeling is currently in its infancy in Lesotho but offers huge potential. Its further development and extension to include the water cycle is a priority for research.
  - It is vital that studies quantify the uncertainty due to physical, biological and socio-economic processes in order to provide firmly based and useful information on agricultural climate change impacts (Slingo et al., 2005).

(b) Agricultural research
  - More studies on the effects of rising levels of CO_2 and O_3 on crops under field conditions are needed.
  - Defining critical temperatures and their timing within the growing season is needed since the results reveal that high-temperature events are likely to be major impacts of climate change.
  - There is a need in exploration of what suggested adaptive measures would be efficient for either Lesotho farmers or Lesotho government. This may include research on high yielding, nutritive, fast maturing, water efficient and pest and disease resistant varieties of various crops especially vegetables.

(c) Climate modeling
  - There is still a need of improved research weather and climate forecasting. This could be achieved through the use of local scientists to evaluate the current performance of climate simulations and of monthly and seasonal forecasts in their regions
  - Apart from this study, further analysis is required on the simulated precipitation as to its variability and extremes such as number of wet days, number of consecutive dry days, the frequency and intensity of precipitation events.
  - It would be useful to explore the effects of CO_2 fertilization that are likely to be realized in practice.

REFERENCES

AAC, 2002. '**Climate change and Agriculture in Africa. Welcome to Climate Change and Agriculture in Africa'**. Facts about Africa Agriculture Climate. http://www.ceepa.co.za/Climate_Change/index.htm (Accessed date: 1st January, 2010).

Adler, P. R., Grosso, S. J., and Parton W. J. 2007. '**Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems'.** *Ecol. Appl.*17. pp 675 691.

Ahrens, C., 2009. '**Meteorology Today: An Introduction to weather'**. (9th ed.). St. Paul. MN West Publishing Company.

African Agriculture, News, views about agriculture in Africa and beyond. http://www.africanagricultureblog.com/ (Accessed: 31/November/2010).

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M., 1998. '**Crop evapotranspiration – Guidelines for computing crop water requirements'**. *FAO Irrigation and drainage* :56. Food and Agriculture Organization. Rome, Italy.

Alley, R., et al. 2007. Climate Change 2007: The Physical Science Basis. '**Summary for Policymakers. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change'.** *Cambridge University Press, Cambridge UK.*

Bassam, N.E. 2010. **'Handbook of Bioenergy Crops: A complete reference to species, Development and applications'**. Earthscan Ltd, London.

Benhin, J.K.A. 2006. **'Climate change and South African agriculture: impacts and adaptation options'**. *CEEPA Discussion Paper*, 21. pp 78.

Betts, R. 2005. **'Integrated approaches to climate-crop modeling: needs and challenges'**. *Phi. Trans.R.Soc.* B360, pp 2049-2065.

Bird, I. F., Cornelius, M. J., and Keys, A. J. 1977. **'Effects of Temperature on Photosynthesis by Maize and Wheat'.** *J. Exp. Bot.* 28, pp519-24.

Bhadwal, S. 2006. '**Indicators of Adaptive Capacity. Mapping climate vulnerability and poverty in Africa: where are the hot spots of climate change and household vulnerability? International livestock research institute'**.

Boko, M., Niang, I., Nyong, A., Vogel, C., Githeko, A., Medany, M., Osman-Elasha, B., Tabo, R., and P. Yanda, 2007. Africa: **'Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change'**, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., *Cambridge University Press, Cambridge UK*, pp 433-467.

Bony, S., 2006. **'How well do we understand and evaluate climate change feedback processes'?** J. Clim., in press.

Boote, K.J., Sinclair, T.R. 2006. '**Crop physiology: significant discoveries and our changing perspective on research**'. *Crp. Science* 46, pp2270–2277.

Burea Of Statistics. 2008. Crop Forecasting http://www.bos.gov.ls/New%20Folder/Copy%20of%20Agriculture/2008-09_Crop%20forecasting_Report.pdf (Accessed: 11/October/2010)

Carbone, G., Kiechle, W., Locke, L., Mearns, L., McDaniel, L., Downton, M. 2003. '**Response of soybeans and sorghum to climate change scenarios in the southeastern United States'**. *Clim. Change*, 60, pp73-98.

Chipanshi, A.C, Ripley, E.A., Lawford, R.G. 1999. **'Large-scale simulation of wheat yield in semi-arid environments using crop-growth model'**. *Agron Syst* 59. pp57–66.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr A., and Whetton, P. 2007: Regional Climate Projections. In: '**Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change'.** [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Dawyer, S.A., Ghannoum, O., Nicotra, A., and Caemmerer, S.V., 2006. **'High temperature acclimation of C_4 photosynthesis is linked to changes in photosynthetic biochemistry'**. Molecular Plant Physiology Group, Research School of Biological Sciences and School of Botany and Zoology, Australian National University, Australia.

De Jager, J.M., and Schulze , R.E. 1977. **'The broad geographic distribution in Natal of Climatological factors important to agricultural planning'**. *Agrochemophysica* 9, pp81 – 91.

Dobie, P., Barry S., Patrick, W., and Mark, W., 2008. **"How do Poor People Adapt to Weather Variability and Natural Disasters Today?"** *Human Development Report: Fighting Climate Change:* Human Solidarity in a Divided World.

De Silva, C.S, Weatherhead, E.K., Knox ,J.W., and Rodriguez-Diaz, J.A. 2007.'**Predicting the impacts of climate change – A case study of paddy irrigation water requirements in Sri Lanka'**. *Agricultural Water Management* 93. pp19–29.

Doria, R., Madramootoo, C.A., Medhi, and B.B. 2007. '**Estimation of future crop water requirements for 2020 and 2050, using CROPWAT'**. *IEEE.*, 4057324.

Erda, L., Wei, X., Hui, J., Yinlong, X., Yue, L., Liping, B., and Liyong, X. 2005. **'Climate change impacts on crop yield and quality with CO2 fertilization in China**'. *Phil. Trans. R.Soc.* B 360, pp 2149–2154.

Environmental Protection Agency (EPA), 1992. **'Agriculture.Climate Change Discussion Serie**s'. United States Environmental Protection Agency. Office of Policy, Planning and Evaluation. pp 2.

Eyring, V., et al. 2005a. **'A strategy for process-oriented validation of coupled chemistry climate models',** *Bull. Am. Meteorol. Soc*., 86, pp1117– 1133.

FAO. 2003. **'World agriculture: Towards 2015/2030'**. An FAO Perspective. http://www.fao.org/DOCREP/005/Y4252E/Y4252E00.HTM (Accessed date: 4/February/2010).

FAO 2006. **'CROPWAT Model'**. Food and Agriculture Organization. Rome, Italy.

FAO. 2007. FAO Global information and early warning system on food and agriculture world food programme: **'FAO/WFP Crop and food supply assessment mission to Lesotho'**. http://www.fao.org/docrep/010/ah865e/ah865e00.HTM (Accessed date: 4/ July/2010).

FAO. 2009. **'The State of Food and Agriculture'**. Food and Agriculture Organization of the United Nations, Rome, pp 211.

Fischer G., M. Shah, F.Tubiello, and H.van Velthuizen. 2005. '**Socio-econoomic and climate change impacts on agriculture: An integrated assessment, 1990-2080'**. *Philos. Trans. R. Soc. Ser. B* 360: pp2067–2083.

Garnaut, R. 2008. The Garnaut Climate Change Review. Cambridge University Press. Australia.

Hargreaves, G.H., and Allen, R.G. 2003. **'History and evaluation of Hagreaves evapotranspiration equation'.** *J. Irrig. Drain.Eng*. 129, pp 53-63.

Harvey,D., Gregory, J.M., Hoffert, M., Jain, A., Lal, M., Leemans, R., Raper, S., Wigley, T.M.L., and de Wolde, J., 1997. **'An introduction to simple climate models used in the IPCC Second Assessment Report**'. IPCC Technical Paper II, Intergovernmental Panel on Climate Change, Geneva, Switzerland, pp 47**.**

Hernes, H., Dalfelt, A., Berntsen, T., Holtsmark, B., Otto Naess, L., Selrod, R., and Aaheim, A., 1995. **'Climate strategy for Africa'**. *CICERO Report 1995*:3, University of Oslo.

Holmén, H. 2003. **'Reflections on natural reconditions for a green revolution in Africa**, Department of Geography. Linkoping University, The Tema Institute, SE-581 83. Linkoping Sweden.

Hoogenboom, G. 2000. **'Contribution of agrometeorology to the simulation of crop production and its applications'**. *Agric. and Forest Meteoro.l* 103, pp137-157.

Hudson, D.A., and Jones, R.G. 2002. **'Regional climate model simulations of present day and future climates of Southern Africa'**. *Technical Note* 39, Hadley Centre, Bracknell, pp 42.

Hulme, M., Wigley, T., Barrow, E., Raper, S., Centella, A., Smith, S. and Chipanshi, A.C. 2008. '**Using a climatic scenario generator for vulnerability and adaption assessments: MAGICC and SCENGEN version 5.3 workbook'**. Norwich, England. Climatic Research Unit.

Hydén, L. 1996a. **'Meteorological Droughts and Rainfall Variability in the Lesotho Lowlands'**. Licentiate Thesis, Div. of Hydraulic Eng., Dept. of Civil and Environ. Eng. *Royal Inst. Of Technol*., Stockholm. pp 139.

Hydén, L. 2002. **'The influence on summer rainfall in the Lesotho Lowlands from Indian Ocean SSTs'.** Nord Hydrol 33:305–318

ICRISAT, 1980. '**Climatic classification: a consultant's meeting',** 14-16 April 1980. Patancheru, Andhra Pradesh, India**.** p 1 – 149.

International Institute of Tropical Africa (IITA), 2002. Maize. http://www.iita.org/crop/maize.htm (Accessed: 20/August/2010).

Integrated Regional Information Networks reports http://www.irinnews.org/report.aspx?ReportId=86910 (Accessed: 2/October/2010)

Igyor, M.A, Ogbonna, A.C. ,and Palmer, G.H.,1998. **'Effect of malting temperature and time on enzyme development and sorghum properties'.** *J. of Inst. Brewing* 2, pp101–104.

McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., and White, K.S. (Eds). 2007. **'Climate Change 2007: Impacts, Adaptation, and Vulnerability'**, Contribution of Working Group II to the Forth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge: Cambridge University Press.

Japtap, S.S., Jones, J.W. 2002. **'Adaptation and evaluation of the CROPGRO-soybean model to predict regional yield and production'**. *Agric. Ecosys. Environ*. 93. pp73–85.

Jayamaha, G.S. 1979. **'A contribution to the study of the Weather and Climate of Lesotho with Special Reference to the Agrometeorology in the Country'**. Lesotho Government Printer. pp 56.

Jenkins, G., and Lowe, J. 2003. **'Handling uncertainties in the UKCIP02 scenarios of climate change. Hadley Centre technical note'**, vol. 44. Exeter, UK: Met Office.

Jones, P. G., and Thornton, P. K. 2003. **‘The potential impacts of climate change on maize production in Africa and Latin America in 2055’**. *Global Environ. Change* 13, pp51–59.

Joubert, A.M., and Hewitson, B.C. 1997. **‘Simulating present and future climates of southern Africa using general circulation models’.** *Prog. in Phys. Geogr*., 21, 51-78.

Karanja, F.K. 2006. **‘CROPWAT model analysis of crop water use in six districts in Kenya’**. CEEPA DP35, University of Pretoria, South Africa pp 14-18.

Kimball, B.A., Kobayashi, K., and Bindi, M. 2002. **’Responses of agricultural crops to free-air CO_2 enrichment**. *Advances in Agronomy* **77**. pp 293–368.

Kim, S. H., Gitz, D. C., Sicherb, R. C., Baker, J. T., Timlin, D. J., and Reddy, V. R. 2007. **‘Temperature dependence of growth, development, and photosynthesis in maize under elevated CO_2’**. *Environ. Exp. Bot.* 61, 224–236.

Kreslavski, V.D., Carpentier, R., Klimov, V.V., Murata, N., and Allakhverdiev, S.I. 2007. **‘Molecular Mechanisms of Stress Resistance of the Photosynthetic Apparatus’**. Institute of Basic Biological Problems, Russian Academy of Sciences, Pushchino. Moscow oblast

Kruger, A.C. and S. Shongwe, 2004. **‘Temperature trends in South Africa 1960– 2003’**. *Int. J. Climatol.*, 24, pp 1929-1945.

Lebel, T., Delclaux F., Le Barbe L., and Polcher J. 2000. **‘From GCMscales to hydrological scales: rainfall variability in West Africa’.** *Stoch. Env. Res. Risk A.*, 14, pp 275-295.

Lesotho Vulnerability Assessment Committee (LVAC), 2007. ‘**Livelihood Vulnerability Assessment Report May 2007’**. Maseru, Lesotho.

LMS, Ministry of natural resources, 2000. ‘**Vulnerability Assessment Report- UNEP/GEF Climate Change Study in Lesotho’.**
http://unfccc.int/ttclear/pdf/TNA/Lesotho/TNA%20report%20lesotho.pdf
(Accessed: 13/ April /2010).

Low, A.B., and Rebelo, T.G. 1996. **‘Vegetation of South Africa, Lesotho and Swaziland’**. Pretoria: Department of environmental Affairs & Tourism

Lutz, W., Sanderson, W., and Scherbov, S. 2001. ‘The end of world population growth’. *Nature* 412, pp543-545.

Magorokosho, C., Warburton, M., Banziger, M., Betran, J., and Dreisigacker, S. 2007. **‘The Introduction of Maize in Africa and Current Levels of Diversity in Zimbabwe, Zambia and Malawi’**. Botanical Society of America.
http://www.2007.botanyconference.org/engine/search/index.php?func=detail&aid=953
(Accessed date: 11/March/2010)

Marake, M.V. 1999. ‘**Arable Agriculture’**. Chakela, Q.K. (Ed). ‘State of environment in Lesotho’.

Matarira, C.H., Makadho, J.M. and Mwamuka, F.C. 1995. **‘Zimbabwe: Climate Change Impacts on Maize Production and Adaptive Measures for the Agricultural Sector’**. Interim Report on Climate Change Country Studies, Country Studies Program, U.S.

Mayet, M. 2005. ‘**Comments on Lesotho’s Biosafety Bill’.** African Centre for Biosafety. http://www.biosafetyafrica.net/_DOCS/ACB_Comments_Lesotho.pdf (Accessed 28/October/2010).

McMaster, G.S., White, J.W., Hunt, L.A., Jamieson, P.D., Dhillon, S.S., and Ortiz- Monsterio, J.I. 2008. **‘Simulating the influence of vernalization, photoperiod and optimum temperature on wheat developmental rates’**. *Ann. Bot* 102, pp561–569.

Mendelsohn, R., Dinar, A., Dalfelt, A. 2000. ‘**Climate Change Impact On African Agriculture’**,World Bank.

Mendelsohn, R., Dinar, A., and Sanghi, A. 2001. **"The Effect of Development on the Climate Sensitivity of Agriculture",** *Environment and Development Economics,* 6, pp. 85-101.

Moonen, A.C., Ercoli, L., Mariotti, M. and Masoni, A. 2002. **‘Climate change in Italy indicated by agrometeorological indices over 122 years’.** *Agric. and Forest Meteorol.* 111. pp13-27.

Nakicenovic, N., (ed.), 2000. **‘Greenhouse gas emissions scenarios’**. *Technological Forecasting & Social Change*, 65, pp3.

Nakicenovic, N. et al. 2003. IPCC SRES revisited: a response. Clim. Change 14, pp187–214.

Nortes, P.A., Gonzalez-Real, M.M., Egea, G., Baille A. 2009. **‘Seasonal effects of deficit irrigation on leaf photosynthetic traits of fruiting and non-fruiting shoots in almond trees’.** *Tree Physiol* 29. pp375–388

OTA, 1993**. ‘Preparing for an Uncertain Climate: Summary. Office of Technology Assessment’**, United States Congress.OTA,5, 63.pp 63.

Osborne, T. M. 2005. **‘Towards an Integrated approach to simulating crop-climate interactions’**. Ph.D thesis, University of reading.

Osbahr, H. 2007. **‘Building Resilience: Adaptation Mechanisms and Mainstreaming for the Poor’.** *Fighting Climate Change: Human Solidarity in a Divided World*. Human Development Report Office. New York: UNDP.

Parry, M. L., and Duinker, P. N. 1990**."Agriculture and Forestry".** In: W. J. McG. Tergart, G.

W. Sheldon and D. C. Griffiths, 1990. Climate Change-The IPCC Impacts Assessment.WMO/UNEP Intergovernmental Panel on Climate Change. Canberra: Australian Government Publishing Service. pp 45.

Ramadoss, M., Birch, C.J., Carberry, P.S., and Robertson, M. 2004. **‘Water and high temperature stress effects on maize production’.** The University of Queensland, Gatton Campus, Lawes, 4343. Agricultural Production Systems Research Unit / CSIRO, Toowoomba

Reason, C.J.C., Hachigonta, S., and Phaladi, R.F. 2005. ‘**Interannual variability in rainy season characteristics over the Limpopo region of southern Africa’.** *Int. J.Climatol.*, 25, pp1835-1853.

Ringius, L., Downing, T.E., Hulme, M., Waughray, D., Selrod, R. 1996. **‘Climate change in Africa-issues and regional strategy’**. CICERO Report No. 1996:8, CICERO, Oslo

Rosenzweig, C., Parry, M.L., Fischer, G., and Frohberg, K. 1993. **‘Climate Change and World Food Supply’**. Environmental Change Unit Research: 3, University of Oxford.

Sage, R.F., and Kubien, D.S. 2007. **‘The temperature response of C3 and C4 photosynthesis’**. Department of Ecology and Evolutionary Biology, University of Toronto, Canada and Department of Biology, University of New Brunswick, 10 Bailey , Canada

Saji, N. H., Goswami, B.N., Vinayachandran, P. N., Yamagata, T. 1999. **‘A dipole mode in the tropical Indian Ocean’**. *Nature* 401: pp 360-363.

Santer, B.D., et al. 2005. **‘Amplification of surface temperature trends and variability in the tropical Atmosphere’.** *Science*, 309, pp1551-1556.

Schlenker, W., and Roberts, M.J. 2006. **‘Nonlinear Effects of Weather on Corn Yields’.** *Review of Agricultural Economics*, 28, pp391–8.

Schmitz, G. ,and Rooyani, F. 1987. **‘Lesotho, Geology, Geomorphology, Soils’**. NUL.

Schulze, R.E., Maharaj, M., Lynch, S.D., Howe, B.J. and Melvil-Thomson, B. 1997. South African Atlas of Agrohydrology and Climatology. Water Research Commision, Pretoria, Report TT82/96. 277pp.

Semenov, M. A., and Porter, J. R. 1995. **‘Climatic variability and the modelling of crop yields’**. *Agr. Forest Meteorol*, 73, pp265–283.

Slingo, J.M,. Challinor, A.J., Hoskins, B.J., Wheeler, T.R. 2005. **‘Introduction: food crops in a changing climate’.** *Philos Trans R Soc Lond B Biol Sci.*;360. pp1983–1989.

Smith, P., et al. 2008. ‘**Greenhouse gas mitigation in agriculture’**. *Philos. Trans. R. Soc. B*,. 363(1492): p. 789-813.

Smit, B., and Skinner, M.W. 2002. **‘Adaptation Options in Agriculture to Climate Change: A Typology’** *Mitigation and Adaptation Strategies for Global Change***,** 7, pp 85-114.

Smith, B.J. 2003. **‘Climate Change, adaptive capacity and development’**. London, Imperial College Press.

Soil Classification Working Group. 1991. ‘**Soil classification. A taxonomic system for South Africa’.** Memoirs Agric. Nat. Res. South Africa 1. Dept. Agricultural Development, Pretoria

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M.and Miller, H.L. (eds.). Summary for Policymakers. In: Climate Change 2007. ‘**The Physical Science Basis’. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change’** Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Soussana, J. F., Graux, A. I., and Tubiello, F. N. 2010. **‘Improving the use of modelling for projections of climate change impacts on crops and pastures’**. *J. of Exp. Botany*, 61, pp2217–2228.

Southworth, J., Randolph, J. C., Habeck, M., Doering, O. C., Pfeifer, R. A., Rao, D. G. and Johnston, J. J. 2000. **‘Consequences of future climate change and changing climate variability on Maize yields in the Midwestern United States’**. *Agric. Ecosyst. Envion*. 82, pp139-158.

Stancalie, G., Adriana, M., and Leonidas, T. 2010. **‘Using earth observation data and CROPWAT model to estimate the actual crop evapotranspiration’**. *Physics and Chemistry of the Earth* 35, pp 25–30

Stewart, J.L., Hanks, R.J., Danielson, R. E., Jackson, E.B., Pruitt, W.O., Franklin, W.T., Riley, J.P. and Hagen, R.M. 1977. **‘Optimizing crop water production through control of water and salinity levels in the soil’.** Utah Water Res Lab Rep PRWG151-1. UTAH State University, Logan.

Stewart, D.W., Dwyer, L. M., and Carrigan, L.L. 1997. **‘Phenological Temperature Response of Maize’**. Canada. Pioneer Hybrid Int., Plant Breeding Div., Willmar, MN 56201

Stige, L.C., Stave J., Chan K.S., Ciannelli L., Pretorelli N., Glantz M., Herren H.R. and Stenseth N.C., 2006. **‘The effect of climate variation on agro-pastoral production in Africa’**. *P. Natl. Acad. Sci. USA*, 103, pp3049-3053.

Stone, R. C. and Meinke, H. 2005. **‘Operational seasonal forecasting of crop performance’.** *Phil. Trans. R. Soc.* B360, pp2109-2124

Tadross, M.A., Hewitson ,B.C., and Usman ,M.T. 2005a. **‘The interannual variability of the onset of the maize growing season over South Africa and Zimbabwe’**. *J. of Clim*., 18, pp3356-3372.

Tingem, M., and Rivington, M. 2009. **‘Adaptation for crop agriculture to climate change in Cameroon’**. Turning on the heat, *Mitigation and Adaptation Strategies for Global Change*, 14, pp.153-168

Todd, M., and Washington, R., 1999. **'Circulation anomalies associated with tropical-temperate troughs in southern Africa and the south west Indian Ocean'**. *Climate Dynamics*, 15, pp937-951.

Todd, M., Washington, R., and Palmer, P. 2004. **'Water vapour transport associated with tropical temperate trough systems over southern Africa and the southwest Indian Ocean'**. *Int. J. of Climatol.*, 24. pp555-568.

Toit, A.S.D., Prinsloo, M.A., Durand, W., and Kiker, G. 2000. **'Vulnerability of maize production to climate change and adaptation assessment in South Africa'.**

Trenberth, K.E., Jones P.D., Ambenje P., Bojariu R., Easterling D., Klein Tank A., Parker D., Rahimzadeh F., Renwick J.A., Rusticucci M., Soden B. and Zhai P., 2007. '**Observations: Surface and Atmospheric Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change'**. [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Tucker, C.J., Dregne, H.E., and Newcomb, W.W. 1991. **'Expansion and contraction of the Sahara desert from 1980 to 1990'**. *Science*, 253, pp299-301.

Tubiello, F. N., and Ewert, F. 2002. **'Modeling the effects of elevated CO2 on crop growth and yield'**: A review. *Eur. J. Agr.* 18, pp57–74.

Verdin, J., Funk, C., and Choularton, G.R. 2005. **'Climate science and famine early warning'**. *Philos Trans R Soc Ser B* 360: pp2155–2168.

Wang, Y.M., Traore, S., and Kerh, T. 2008. **'Computing and Modeling for Crop Yields in Burkina Faso Based on Climatic Data Information'**. *WSEAS Transactions on Information Science and Applications*, 5, pp. 832-842.

Webster, P.J., Moore, A. M., Loschnigg, J.P., and Leben, R.1999. **'Coupled Ocean-atmosphere dynamics in the Indian Ocean during 1997-98'**. *Nature* 401, pp356-360

Wigley, T.M.L. 2008. '**MAGICC/SCENGEN 5.3: User Manual (Version 2)'.** http://www.cgd.ucar.edu/cas/wigley/magicc (Accessed: 10/March/2010)

Wolfe, D.W., Ziska, L., Petzoldt, C., Seaman, A., Chase, L., Hayhoe, K. 2008. **'Projected change in climate thresholds in the Northeastern U.S.: implications for crops, pests, livestock, and farmers'**. *Mitig Adapt Strategies Glob Chang.* 13, pp555–575

World Bank, 2006. '**Climate Change and African Agriculture'.** Policy note number 27. CEEPA.

World food Programme, 2007. **'Food Shortages in Lesotho'**. The facts http://www.wfp.org/stories/lesotho-farmers-find-key-brighter-future-wfp (Accessed date: 5/April/2010).

Wheeler, T.R., Crawford, P.Q., Ellis, R.H., Porter, J.R. and Prasad, P.W., 2000. **'Temperature variability and the yield of annual crops'.** *Agric., Ecosys. and Environ.*, **82**, 159–167.

WHO, 2007. **'Health and global Environmental Change'**. Series No.1. Methods of assessing human health vulnerability and public health adaptation to climate change.

World Population Prospects, 2008 http://esa.un.org/unpp/p2k0data.asp (Accessed: 20/April/2010)

Yohe, G., and Tol, R.S.J. 2001. **'Indicators for Social and Economic Coping Capacity – Moving Toward a Working Definition of Adaptive Capacity**'. Department of Economics ,Wesleyan University, Middletown Germany.

Xiong, W., Matthews, R., Holman,I., Lin, E., Xu, Y. 2007. **'Modelling China's potential maize production at regional scale under climate change'**. *Climatic Change* 85, pp433–451.

Ziervogel, G. 2004. **'Targeting seasonal climate forecasts for integration into household level decisions:the case of smallholder farmers in Lesotho'**. *Geo. J.*, 170, pp6–21.

Zhang, G.H., Fu, S.H., Fang, W.H., Imura, H., and Zhang, X.C. 2007. **'Potential effects of climate change on runoff in the Yellow River basin of China'**. *Transactions of the ASABE* 50. pp911–918.

APPENDIX: A

Table 1: District profiles.

Agricultural district	Longitude (East)	Latitude (South)	Altitude(m)
Leribe	28°0'0"	29°0'0"	1740
	28.0°	-29°	
Maseru	27°29'16"	29°19'19"	1628
	27.48°	-29.32°	
Mohales'Hoek	27°40'0"	30°10'0"	1620
	27.66°	-30.17°	

Table 2: Climatic parameters of Leribe (1980-2008).

Month	T_{max}(°C)	T_{min}(°C)	Rainfall(mm)
Jan	29.9	11.2	113.5
Feb	25.7	13.0	97
Mar	26.8	10.9	99
Apr	20.9	8.7	57.7
May	17.6	7.5	23.1
Jun	15.6	-0.5	12.8
Jul	16.1	1.9	8.7
Aug	17.3	1.4	27.2
Sep	23.3	4.1	33.1
Oct	23.5	6.9	68.1
Nov	25.4	10.7	80.8
Dec	26.4	11.8	99.6

Table 3: Climatic parameters of Maseru (1980-2008).

Month	T_{max}(°C)	T_{min}(°C)	Rainfall(mm)
Jan	30.3	14.3	107.3
Feb	26.7	14.5	91.9
Mar	24.7	12.8	96.4
Apr	19.8	8.4	51.9
May	18.5	3.4	24.7
Jun	14.1	-0.3	11
Jul	16.2	-0.8	7.8
Aug	19.7	2.1	20.5
Sep	20	6.7	32.7
Oct	20.5	9.7	74.1
Nov	24.1	11.6	80.4
Dec	24.7	14.6	89.3

Table 4: Climatic parameters of Mohales'Hoek (1980-2008).

Month	T_{max}(°C)	T_{min}(°C)	Rainfall(mm)
Jan	32.2	14.9	111.1
Feb	30.3	14.8	101.4
Mar	24.1	12.8	96.8
Apr	21.1	6.8	60.3
May	17.4	4.3	19.5
Jun	15.8	0.8	17.1
Jul	17.9	0.6	10.1
Aug	19.6	4.3	29.0
Sep	22.3	6.7	38.1
Oct	22.9	7.8	72.9
Nov	27.2	10.5	74.8
Dec	29.8	12.0	88.4

APPENDIX: B

Table 5: SRES scenario quantifications (Christensen et al., 2007) numbers are for 2100.

	Storyline	
	A2	B2
Population growth	High	Medium
	≈ 15 billion	≈ 10 billion
GDP growth	Medium	Medium
	243	235
GDP per capita	Ind: US$46,200	Ind: US$54,400
	Dev.:$11,00	Dev.: US$ 18,000
Energy use	High	Medium
Land Use Changes	Medium-high	Medium
		Cropland +22%
		Forest +5%
Resource availability	Low	Medium
Pace and direction of technological change	Slow	Medium
Favoured energy	Regional diversity	'Dynamics as usual'

Table 6: The models used in this paper and the summary of their included radiative forcings (indicated by a "Y"), following Santer et al. (2005): well-mixed greenhouse gases (G), tropospheric and stratospheric ozone (O), sulfate aerosol direct effects (SD); sulfate aerosol indirect effects (SI), black carbon (BC), organic carbon (OC), mineral dust (MD), sea salt (SS), land use change (LU), solar irradiance (SO), volcanic aerosols (VL), and volcanic aerosols modeled as a solar constant change (Y). (Further model details can be found online at* (http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php).

AOGCM	G	O	SD	SI	BC	OC	MD	SS	LU	SO	VL
CCCMA	y	y	y	-	y	y	-	-	-	y	y
GFDL-CM2.1	y	y	y	-	y	y	-	-	y	y	y
GISS-EH	y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
UKHADCM3	Y	Y	Y	Y	-	-	-	-	-	-	-

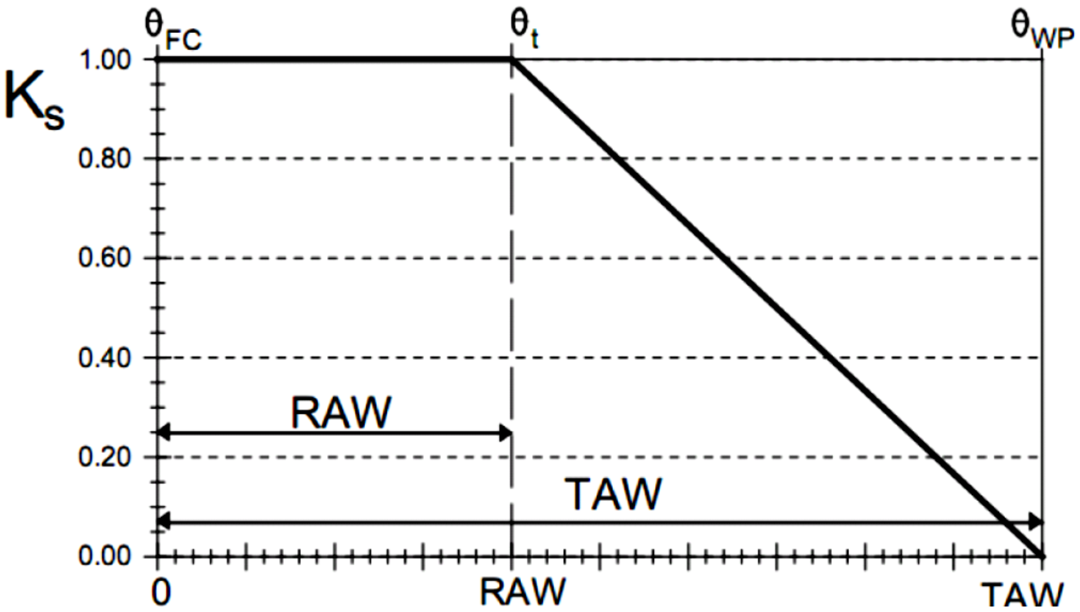

Figure1: Water stress coefficient (Ks) as a function of total available water (TAW) and readily available water (RAW) (Allen et al., 1998).

APPENDIX: C

Table 7: Estimated variables used to assess yield reduction in Leribe district for (a) A2 scenario and (b) B2 scenario

(a)

CROP	Models	Year	Ym	Ky	ETo(max)	ETc	Ks	Ya
MAIZE	GFDL	2050	4.55	1.25	428	285	0.946	4.243
		2100	4.55	1.25	462	288	0.920	4.095
	CCCMA	2050	4.55	1.25	507	365	0.930	4.150
		2100	4.55	1.25	597	412	0.909	4.032
	GISS-EH	2050	4.55	1.25	492	290	0.919	4.089
		2100	4.55	1.25	583.	409	0.903	3.998
	UKHADCM3	2050	4.55	1.25	427	276	0.940	4.209
		2100	4.55	1.25	462	291	0.919	4.089
WHEAT	GFDL	2050	4.09	1.15	428	234	0.938	3.798
		2100	4.09	1.15	456	321	0.892	3.582
	CCCMA	2050	4.09	1.15	507	369	0.902	3.629
		2100	4.09	1.15	597	473	0.838	3.328
	GISS-EH	2050	4.09	1.15	492	350	0.894	3.591
		2100	4.09	1.15	583	489	0.826	3.273
	UKHADCM3	2050	4.09	1.15	427	251	0.920	3.714
		2100	4.09	1.15	462	356	0.902	3.629
SORGHUM	GFDL	2050	3.632	0.9	428	176	0.951	3.470
		2100	3.632	0.9	462	199	0.892	3.279
	CCCMA	2050	3.632	0.9	507	299	0.900	3.306
		2100	3.632	0.9	597	328	0.882	3.246
	GISS-EH	2050	3.632	0.9	492	295	0.910	3.338
		2100	3.632	0.9	583	403	0.842	3.116
	UKHADCM3	2050	3.632	0.9	427	154	0.941	3.439
		2100	3.632	0.9	462	178	0.910	3.338

(b)

CROP	Models	Year	Ym	Ky	ETo(max)	ETc	Ks	Ya
MAIZE		2050	4.55	1.25	350	256	0.969	4.374
	GFDL	2100	4.55	1.25	392	269	0.949	4.260
		2050	4.55	1.25	361	266	0.958	4.311
	CCCMA	2100	4.55	1.25	458	384	0.928	4.141
		2050	4.55	1.25	427	272	0.943	4.226
	GISS-EH	2100	4.55	1.25	491	390	0.908	4.026
		2050	4.55	1.25	380	269	0.961	4.328
	UKHADCM3	2100	4.55	1.25	402	376	0.943	4.226
WHEAT		2050	4.09	1.15	350	269	0.942	3.817
	GFDL	2100	4.09	1.15	392	297	0.902	3.629
		2050	4.09	1.15	391	296	0.922	3.723
	CCCMA	2100	4.09	1.15	458	319	0.900	3.621
		2050	4.09	1.15	427	313	0.930	3.761
	GISS-EH	2100	4.09	1.15	491	359	0.901	3.622
		2050	4.09	1.15	380	281	0.943	3.822
	UKHADCM3	2100	4.09	1.15	402	317	0.910	3.667
SORGHUM		2050	3.632	0.9	350	241	0.960	3.501
	GFDL	2100	3.632	0.9	392	268	0.902	3.311
		2050	3.632	0.9	391	271	0.924	3.382
	CCCMA	2100	3.632	0.9	458	389.	0.879	3.237
		2050	3.632	0.9	427	281	0.925	3.385
	GISS-EH	2100	3.632	0.9	491	396	0.870	3.207
		2050	3.632	0.9	380	255	0.970	3.534
	UKHADCM3	2100	3.632	0.9	402	373	0.940	3.436

Table 8: Estimated variables used to assess yield reduction in Maseru district for (a) A2 scenario and (b) B2 scenario.

(a)

CROP	Models	Year	Ym	Ky	ETo(max)	ETc	Ks	Ya
MAIZE	GFDL	2050	1.452	1.25	430	329	0.861	1.200
		2100	1.452	1.25	470	358	0.796	1.082
	CCCMA	2050	1.452	1.25	503	352	0.848	1.176
		2100	1.452	1.25	589	490	0.789	1.069
	GISS-EH	2050	1.452	1.25	497	365	0.843	1.167
		2100	1.452	1.25	599	495	0.778	1.049
	UKHADCM3	2050	1.452	1.25	429	316	0.859	1.196
		2100	1.452	1.25	465	355	0.791	1.071
WHEAT	GFDL	2050	1.182	1.15	430	388	0.932	1.087
		2100	1.182	1.15	470	372	0.902	1.049
	CCCMA	2050	1.182	1.15	503	450	0.880	1.019
		2100	1.182	1.15	589	565	0.860	0.992
	GISS-EH	2050	1.182	1.15	497	462	0.870	1.005
		2100	1.182	1.15	599	580	0.830	0.951
	UKHADCM3	2050	1.182	1.15	429	346	0.920	1.073
		2100	1.182	1.15	465	378	0.890	1.032
SORGHUM	GFDL	2050	2.238	0.9	430	354	0.907	2.051
		2100	2.238	0.9	470	378	0.860	1.956
	CCCMA	2050	2.238	0.9	503	479	0.890	2.016
		2100	2.238	0.9	589	539	0.849	1.934
	GISS-EH	2050	2.238	0.9	497	305	0.870	1.976
		2100	2.238	0.9	599	528	0.840	1.916
	UKHADCM3	2050	2.238	0.9	429	305	0.906	2.048
		2100	2.238	0.9	465	389	0.857	1.950

(b)

CROP	Models	Year	Ym	Ky	ETo(max)	ETc	Ks	Ya
MAIZE	GFDL	2050	1.452	1.25	380	303	0.891	1.200
		2100	1.452	1.25	402	320	0.863	1.082
	CCCMA	2050	1.452	1.25	371	346	0.880	1.176
		2100	1.452	1.25	478	366	0.843	1.049
	GISS-EH	2050	1.452	1.25	425	383	0.879	1.167
		2100	1.452	1.25	499	387	0.839	1.069
	UKHADCM3	2050	1.452	1.25	358	296	0.890	1.196
		2100	1.452	1.25	397	311	0.860	1.071
WHEAT	GFDL	2050	1.182	1.15	380	291	0.935	1.087
		2100	1.182	1.15	402	347	0.892	1.049
	CCCMA	2050	1.182	1.15	371	323	0.898	1.019
		2100	1.182	1.15	478	353	0.876	0.951
	GISS-EH	2050	1.182	1.15	425	313	0.930	1.005
		2100	1.182	1.15	499	439.1	0.877	0.992
	UKHADCM3	2050	1.182	1.15	358	299	0.932	1.073
		2100	1.182	1.15	397	333	0.895	1.032
SORGHUM	GFDL	2050	2.238	0.9	380	345	0.987	2.051
		2100	2.238	0.9	402	393	0.899	1.956
	CCCMA	2050	2.238	0.9	371	351	0.890	2.016
		2100	2.238	0.9	478	389	0.840	1.916
	GISS-EH	2050	2.238	0.9	425	371	0.938	1.976
		2100	2.238	0.9	499	436	0.881	1.934
	UKHADCM3	2050	2.238	0.9	358	241	0.960	2.048
		2100	2.238	0.9	397	268	0.870	1.950

Table 9: Estimated variables used to assess yield reduction in Mohales'Hoek district for (a) A2 scenario and (b) B2 scenario.

(a)

CROP	Models	Year	Ym	Ky	ETo(max)	ETc	Ky	Ya
MAIZE	GFDL	2050	1.813	1.25	528	429	0.891	1.566
		2100	1.813	1.25	556	498	0.810	1.382
	CCCMA	2050	1.813	1.25	607	589	0.838	1.446
		2100	1.813	1.25	692	525	0.786	1.328
	GISS-EH	2050	1.813	1.25	583	402	0.823	1.412
		2100	1.813	1.25	697	602	0.777	1.307
	UKHADCM3	2050	1.813	1.25	527	456	0.892	1.569
		2100	1.813	1.25	562	509	0.809	1.380
WHEAT	GFDL	2050	3.797	1.15	528	381	0.925	3.470
		2100	3.797	1.15	556	400	0.898	3.351
	CCCMA	2050	3.797	1.15	607	481	0.898	3.351
		2100	3.797	1.15	692	565	0.865	3.208
	GISS-EH	2050	3.797	1.15	583	469	0.897	3.347
		2100	3.797	1.15	697	581	0.862	3.194
	UKHADCM3	2050	3.797	1.15	527	396	0.932	3.500
		2100	3.797	1.15	562	406	0.899	3.356
SORGHUM	GFDL	2050	1.22	0.9	528	455	0.953	1.168
		2100	1.22	0.9	556	498	0.876	1.084
	CCCMA	2050	1.22	0.9	607	530	0.890	1.099
		2100	1.22	0.9	692	599	0.844	1.049
	GISS-EH	2050	1.22	0.9	583	516	0.880	1.088
		2100	1.22	0.9	697	579	0.836	1.040
	UKHADCM3	2050	1.22	0.9	527	467	0.952	1.167
		2100	1.22	0.9	562	490	0.897	1.107

(b)

CROP	Models	Year	Ym	Ky	ETo(max)	ETc	Ks	Ya
MAIZE	GFDL	2050	1.813	1.25	460	301	0.897	1.580
		2100	1.813	1.25	483	391	0.868	1.515
	CCCMA	2050	1.813	1.25	471	396	0.888	1.559
		2100	1.813	1.25	488	406	0.839	1.448
	GISS-EH	2050	1.813	1.25	467	373	0.878	1.537
		2100	1.813	1.25	491	432	0.828	1.423
	UKHADCM3	2050	1.813	1.25	450	296	0.898	1.582
		2100	1.813	1.25	463	389	0.870	1.518
WHEAT	GFDL	2050	3.797	1.15	460	311	0.942	3.542
		2100	3.797	1.15	483	407	0.897	3.348
	CCCMA	2050	3.797	1.15	471	400	0.919	3.443
		2100	3.797	1.15	488	423	0.886	3.299
	GISS-EH	2050	3.797	1.15	467	381	0.930	3.491
		2100	3.797	1.15	491	459	0.878	3.263
	UKHADCM3	2050	3.797	1.15	450	299	0.942	3.544
		2100	3.797	1.15	463	393	0.899	3.354
SORGHUM	GFDL	2050	1.22	0.9	460	236	0.987	1.206
		2100	1.22	0.9	483	264	0.939	1.153
	CCCMA	2050	1.22	0.9	471	272	0.899	1.109
		2100	1.22	0.9	488	360	0.864	1.071
	GISS-EH	2050	1.22	0.9	427	282	0.909	1.120
		2100	1.22	0.9	491	396	0.871	1.078
	UKHADCM3	2050	1.22	0.9	450	242	0.986	1.205
		2100	1.22	0.9	463	269	0.937	1.150

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