

**DOWNSCALING CLIMATE CHANGE INFORMATION USING AN ENSEMBLE OF
REGIONAL CLIMATE MODELS FOR AGRICULTURAL PLANNING: A CASE
STUDY OF TANA RIVER COUNTY, KENYA**

KETIEM, PATRICK KIBET

**A Thesis Submitted to the Graduate School in Partial Fulfillment of the Requirements for
the Degree of Doctor of philosophy in Environmental Science of Egerton University**

EGERTON UNIVERSITY

November, 2016

DECLARATION AND RECOMMENDATION

Declaration

This thesis is my original work and has not been presented in any other institution of higher learning for the award of an academic degree.

Signature: -----

Date:-----

Patrick Kibet Ketiem

ND12/0338/12

Recommendation

This thesis has been submitted with our recommendation as University supervisors

Signature: -----

Date:-----

Dr. Makenzi, P.M. (PhD)

Department of Environmental Science, Egerton University,
EGERTON, KENYA

Signature: -----

Date:-----

Dr. Omondi, P.A. (PhD)

IGAD Climate Prediction and Applications Centre (ICPAC)
NAIROBI, KENYA

Signature: -----

Date:-----

Dr. Maranga, E.K. (PhD)

Department of Natural Resources, Egerton University
EGERTON, KENYA

COPYRIGHT

© Patrick K. Ketiem, 2016

All rights reserved. No part of this thesis may be reproduced in whole or in part, stored in any retrieval system or transmitted in any form or means; electronic, photocopying or otherwise without prior written permission from the author or Egerton University.

DEDICATION

To my wife Dorothy and children Shirlyne, Tony and Collins for their love, encouragement, inspiration, support, patience and sacrifices they made throughout the study period.

”

ACKNOWLEDGEMENTS

I wish to acknowledge the support of many institutions and individuals for the accomplishment of the work reported in this thesis. I am grateful to the Kenya Agricultural and Livestock Research Organization for the opportunity granted to pursue this PhD degree through the “*Agricultural Productivity and Climate change in the Arid and Semi-arid Kenya*” project; International Development Research Centre for the project financial support; IGAD Climate Prediction and Application Centre for supporting study downscaling activities through their laboratories; Ministry of Agriculture, Livestock and Fisheries for availing the agricultural production data; Kenya Meteorological Services for providing climate data and Egerton University, Department of Environmental Science for hosting and supporting my study programme. I am sincerely grateful to my supervisors: Dr. P.M. Makenzi, Dr. P.A. Omondi and Dr. E.K. Maranga for their immense technical support and guidance throughout the study period. Their technical guidance, friendship and encouragements were a strong driving force in the preparation of this thesis. I am deeply indebted to the following people; Dr. Jane Wamuongo and Dr. Michael Okoti for the unlimited support through the IDRC-KALRO funded climate change and agricultural productivity project; Dzillambe Kombo, Joseph Swibe, Peter Muriuki, Pius Kibe, Maurice Obima, Peter Macharia, Peter Njuguna and Geoffrey Maina for their unwavering support in field data collection. Their dedication, willingness and sacrifices at times outside their official normal working hours will never be forgotten. I wish to offer my special thanks to the people of Tana River County; County government staff, chiefs, community-headmen, opinion leaders, farmers, pastoralists and any other resource persons I interacted with during the study for accepting to spare their time, observations, experiences and perceptions. I am indebted to my fellow students within and outside the department of environmental science, Egerton University who spared their time to provide relevant information, drew my attention to new publications, clarified certain technical issues and shaped my thoughts whenever necessary. Finally, my deepest appreciation goes to my family, parents and community for the many sacrifices, inconveniences and support made during the study period. To all, may the Almighty God bless you abundantly.

ABSTRACT

The truncated ecosystems of the Tana River County are highly vulnerable to climate change and variability due to their low adaptive capacities and high dependence on climate sensitive resources. Inadequacy of long term climate information is a serious constraint for long-term planning for enhanced food security and minimization of the adverse impacts of climate change and variability. This study was motivated by the need to downscale climate information using modelling procedures based on Regional Climate Models (RCMs). The objectives of the study revolved around evaluations of the performance of Coordinated Regional Climate Downscaling Experiment (CORDEX) RCMs in simulating rainfall and temperature conditions and use of these data sets in projecting future climate change scenarios and their implications on agricultural productivity and related resources. Assessments and validation tests were run to authenticate the plausibility of CORDEX RCMs and the relevance of historical climate data in evaluations of the impact of climate change and variability on agricultural productivity. Agricultural data (crops and livestock) for more than 20 years collected from the Ministry of Agriculture, Livestock and Fisheries (MALF) departments in Tana River County were utilized in the study. The gross yield of five widely grown crops in the region comprising of maize, green grams, rice, cassava and mangoes was collated. Livestock population data for specific livestock species was used. Subjective sampling was applied for three focused group discussions conducted. Bi-variate correlations and simple linear regressions were used to investigate crop/livestock production and rainfall relationships. Combination of dynamical and statistical downscaling approaches were used in RCMs evaluation and projecting the future climate scenarios for Tana River County. RCMs simulated above 84% observed climatology in Tana River County making them valuable tools for agricultural production planning. The ensemble model had better agreement with ground data observations than individual models. Seasonal rainfall variability was of the order of 70% during short and long rains making rainfed agriculture unreliable. Crop yields showed low correlations with March-May (MAM) seasonal rainfall ($r = 0.3$) as compared with October-December (OND) season ($r = 0.55$). Seasonal rainfall explained 8% of the variation in maize yields and 40-56% in livestock numbers. The OND season is more reliable for agricultural production activities in the region. A warming trend in the region of 3.0 to 3.5°C under RCP4.5/8.5 scenarios is projected by the middle of 21st century. A warming climate in the region will negatively impact food production, water availability and livelihood systems in the region.

TABLE OF CONTENTS

TITLE	Error! Bookmark not defined.
DECLARATION AND RECOMMENDATION	ii
COPYRIGHT	iii
DEDICATION.....	iv
ACKNOWLEDGEMENTS	v
ABSTRACT.....	vi
TABLE OF CONTENTS	vi
LIST OF TABLES	xi
LIST OF FIGURES	xii
LIST OF PLATES	xv
LIST OF APPENDICES	xvi
LIST OF ABBREVIATIONS AND ACRONYMS	xvii
CHAPTER ONE	1
1.0 INTRODUCTION.....	1
1.1 Background information	1
1.2 Statement of the problem	3
1.3 Objectives of the study.....	4
1.3.1 Broad objective.....	4
1.3.2 Specific objectives.....	4
1.4 Research hypotheses	4
1.5 Justification of the study	4
1.6 Scope of the study	6
1.7 Study limitations and assumptions.....	7
1.7.1 Study limitations	7
1.7.2 Study assumptions.....	8
1.8 Definition and operationalization of terms.....	9
CHAPTER TWO	13
2.0 LITERATURE REVIEW	13
2.1 Introduction	13

2.2	CORDEX RCMs and their application in climate downscaling	13
2.3	Climate downscaling techniques in the agricultural sector	17
2.4	Characterization of rainfall variability in the eastern Africa.....	19
2.5	Agricultural production and changing change	19
2.6	Climate change projections and agricultural production.....	23
CHAPTER THREE		25
3.0	METHODOLOGY	25
3.1	Introduction	25
3.2	The study area	25
3.2.1	<i>Physical location</i>	25
3.2.2	<i>Demographic characteristics and livelihood sources</i>	27
3.2.3	<i>River Tana basin</i>	28
3.2.4	<i>Climate</i>	29
3.2.5	<i>Vegetation and biodiversity</i>	30
3.2.6	<i>Soils</i>	30
3.3	Study research design.....	31
3.3.1	<i>Case study</i>	33
3.4	Downscaling approaches.....	34
3.4.1	<i>Dynamical downscaling</i>	35
3.4.2	<i>Statistical downscaling</i>	36
3.5	Future projections.....	37
3.6	Data collection.....	38
3.6.1	<i>Climate data</i>	39
3.6.2	<i>Crop and livestock data</i>	41
3.6.3	<i>CORDEX RCMs data</i>	41
3.7	Data sampling.....	42
3.8	Data reliability and validity.....	42
3.9	Data management.....	43
3.10	Data analyses.....	43

CHAPTER FOUR.....	47
4.0 RESULTS AND DISCUSSION	47
4.1 Introduction	47
4.2 The performance of CORDEX RCMs in simulating rainfall and temperature characteristics in Tana River County.....	47
4.2.1 <i>Introduction</i>	47
4.2.2 <i>Performance of CORDEX RCMs in simulating eastern Africa rainfall</i>	48
4.2.3 <i>Performance of CORDEX RCMs in simulating mean annual rainfall cycle over eastern Africa</i>	53
4.2.4 <i>Performance of CORDEX RCMs in simulating large-scale global climate forcing signals</i>	54
4.2.5 <i>Performance of CORDEX RCMs in simulating Tana River County rainfall characteristics</i>	54
4.2.6 <i>Performance of CORDEX RCMs in simulating temperature characteristics</i>	56
4.3 Agricultural production and climate in Tana River County.....	59
4.3.1 <i>Rainfall and temperature homogeneity tests</i>	59
4.3.2 <i>Characterization of climate and relationships to crop and livestock productions in Tana River County</i>	60
4.3.3 <i>Crop production characteristics in Tana River County</i>	72
4.4 Projected climate change scenarios in Tana River County	82
4.4.1 <i>Introduction</i>	82
4.4.2 <i>Projected rainfall changes over eastern Africa and Tana River County</i>	82
4.4.3 <i>Projected temperature changes over eastern Africa and Tana River County</i>	87
4.4.4 <i>Impacts of the projected climate and implications on agricultural production and related land resources in Tana River County</i>	95
4.4.4.3 <i>Impacts and implications on agricultural production and other related land resources in Tana River County</i>	98
CHAPTER FIVE	100
5.0 CONCLUSIONS AND RECOMMENDATIONS.....	100
5.1 Introduction	100

5.2	Conclusions	100
5.3	Recommendations	100
5.3.1	<i>Recommendations to policy makers and planners</i>	101
5.3.2	<i>Recommendations to the National and County governments</i>	101
5.3.3	<i>Recommendations to Kenya Meteorological Services (KMS)</i>	102
5.3.4	<i>Recommendations to farmers and pastoralists</i>	102
5.4	Recommendations for further research	103
	REFERENCES	104
	APPENDICES	125

LIST OF TABLES

Table 1:	Sources of water and their proportions in Tana River County	29
Table 2:	Soil characteristics in Tana River County	31
Table 3:	Summary of statistical data analyses	45
Table 4:	Correlation coefficients of maize and green grams yields (tons/kg) with MAM and OND rainfall at six sites in Tana River County	76
Table 5:	Correlation coefficients of annual crop yields and mean annual rainfall totals at six sites in Tana River County	76
Table 6:	Regression analysis of sheep population changes and rainfall in Garissa	81

LIST OF FIGURES

Figure 1:	Map of Kenya showing the study area.....	26
Figure 2:	Research Design Framework	33
Figure 3:	Schematic illustration of factors in the study case design	34
Figure 4:	Weather stations in Tana River County used in the study	40
Figure 5:	Rainfall characteristics of eastern Africa during MAM rainfall season as simulated by CORDEX RCMs, GPCC and ensemble RCM.....	48
Figure 6:	Rainfall characteristics of eastern Africa during OND rainfall season as simulated by CORDEX RCMs, GPCC and ensemble RCM	49
Figure 7:	Tana River County MAM rainfall characteristics as simulated by CORDEX RCMs, GPCC and ensemble RCM.....	50
Figure 8:	CORDEX models biasness over the eastern Africa and Tana River County during MAM season (1989-2009).....	51
Figure 9:	CORDEX models biasness over the eastern Africa and Tana River County during OND season (1989-2009)	52
Figure 10:	Mean annual rainfall cycle over the equatorial region of eastern Africa as reproduced by CORDEX RCMs, GPCC and ensemble RCM	53
Figure 11:	CORDEX RCMs performance in simulating inter-annual precipitation variability over equatorial sector.....	54
Figure 12:	Observed annual rainfall sequence from the Garissa weather station records.....	55
Figure 13:	Mean surface temperature characteristics of Tana River County and eastern Africa during MAM season as simulated by CORDEX RCMs, GPCC and ensemble RCM.....	56
Figure 14:	Mean surface temperature characteristics of Tana River County and eastern Africa during OND season as simulated by CORDEX RCMs, GPCC and ensemble RCM	57
Figure 15:	Mean surface temperature characteristics of Tana River County during MAM season as simulated by CORDEX RCMs, GPCC and ensemble RCM.....	58
Figure 16:	Cumulative single mass curve for MAM seasonal rainfall over Kipini station....	59
Figure 17:	Cumulative single mass curves for January-December mean minimum (Tmin) surface temperature over Garissa station	60

Figure 18:	Mean annual rainfall in Tana River County	62
Figure 19:	Tana River County MAM rainfall characteristics (a) climatology and (b) CVs ..	63
Figure 20:	Tana River County OND rainfall characteristics (a) Climatology and (b) CVs...	64
Figure 21:	Decadal seasonal rainfall change in Tana River County for (a) MAM and (b) OND seasons.....	65
Figure 22:	Mean annual rainfall cycle in Tana River County	66
Figure 23:	Interannual rainfall variability in Tana River County.....	67
Figure 24:	Summary of the number rainy days from Garissa station.....	68
Figure 25:	Annual rainfall anomalies in Tana River County	69
Figure 26:	Mean (a) MAM (b) OND seasonal surface temperature	70
Figure 27:	Interannual mean minimum and maximum temperature (⁰ C) in Tana River County	71
Figure 28:	Crop types and yields in Tana River County	72
Figure 29:	Annual crop yield variability in the lower Tana basin (1989-2011).....	73
Figure 30:	Annual crop yield anomalies in Tana River County (1989-2011).....	74
Figure 31:	Regression between maize yields and MAM rainfall at Kipini.....	77
Figure 32:	Regression between green grams yields and OND rainfall at Witu	78
Figure 33:	Livestock population trend in the lower Tana	80
Figure 34:	Projected rainfall changes over eastern Africa region and Tana River County (in box) by 2030 in MAM (1 st column), JJAS (2 nd column), and OND (3 rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1 st row), RCP4.5 (2 nd row) and RCP8.5 (3 rd) respectively.....	83
Figure 35:	Projected rainfall changes over eastern Africa region and Tana River County (in box) by 2050 in MAM (1 st column), JJAS (2 nd column), and OND (3 rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1 st row), RCP4.5 (2 nd row) and RCP8.5 (3 rd) respectively.....	84
Figure 36:	Projected rainfall changes over eastern Africa region and Tana River County (in box) by 2070 in MAM (1 st column), JJAS (2 nd column), and OND (3 rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1 st row), RCP4.5 (2 nd row) and RCP8.5 (3 rd) respectively.....	85

Figure 37:	The projected relative precipitation change for MAM (top panel) and OND (bottom panel) over Tana River County (baseline 1971-2000) under RCP 2.6 and RCP 8.5 climate scenarios.	86
Figure 38:	Projected maximum temperature changes over eastern Africa and Tana River County (in grid box) by 2030s in MAM (1 st column), JJAS (2 nd column), and OND (3 rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1 st row), RCP4.5 (2 nd row) and RCP8.5 (3 rd row) respectively.	88
Figure 39:	Projected maximum temperature changes over eastern Africa and Tana River County (in box) by 2050s in MAM (1 st column), JJAS (2 nd column), and OND (3 rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1 st row), RCP4.5 (2 nd row) and RCP8.5 (3 rd row) respectively.	89
Figure 40:	Projected maximum temperature changes over eastern Africa and Tana River County (in box) by 2070s in MAM (1 st column), JJAS (2 nd column), and OND (3 rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1 st row), RCP4.5 (2 nd row) and RCP8.5 (3 rd row) respectively	90
Figure 41:	Projected minimum temperature changes over eastern Africa and Tana River County (in box) by 2030s in MAM (1 st column), JJAS (2 nd column), and OND (3 rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1 st row), RCP4.5 (2 nd row) and RCP8.5 (3 rd row) respectively	91
Figure 42:	Projected minimum temperature changes over eastern Africa and Tana River County (in box) by 2050s in MAM (1 st column), JJAS (2 nd column), and OND (3 rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1 st row), RCP4.5 (2 nd row) and RCP8.5 (3 rd row) respectively	92
Figure 43:	Projected minimum temperature changes over eastern Africa and Tana River County (in box) by 2070s in MAM (1 st column), JJAS (2 nd column), and OND (3 rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1 st row), RCP4.5 (2 nd row) and RCP8.5 (3 rd row) respectively	93
Figure 44:	The projected maximum (top row) and minimum (bottom row) temperature change for MAM (left column) and OND (right column) over the lower Tana basin under RCP 2.6 and RCP 8.5 climate scenarios (baseline 1971-2000)	94

LIST OF PLATES

Plate 1:	River Tana channel diversion at Mnazini area near Garsen town	27
Plate 2:	Research consultative meetings held in Tana Delta Sub-county, February- March, 2012.....	39
Plate 3:	Livestock diversity in the lower Tana basin	79

LIST OF APPENDICES

Appendix 1: Summary of merits and limitations of statistical and dynamical downscaling techniques	125
Appendix 2: Focused Discussion Group and key interview guide	126
Appendix 3: List of weather stations in Tana River County	127
Appendix 4: The status of climate observation station networks in Kenya.....	127
Appendix 5: Summary of drought and extreme rainfall events and the number of people affected in different parts of Kenya (1971-2010)	128
Appendix 6: Annual cost of climate change in Africa in 2030	129
Appendix 7: Tsetse ecological distribution (TED) percentage probability map in Kenya.....	130
Appendix 8: List of CORDEX RCMs and their details.....	131

LIST OF ABBREVIATIONS AND ACRONYMS

A1B	A medium emission scenario
AOGCM	Atmosphere-Ocean Global Circulation Model
AR4	Fourth Assessment Report of the Intergovernmental Panel on Climate
AR5	Fifth Assessment Report of the Intergovernmental Panel on Climate
ARPEGE	Action de Recherche Petite Echelle Grande Echelle model
ASALs	Arid and Semi Arid Lands
AWS	Automatic Weather Station
CIP	Climate Information Portals
CO ₂	Carbon Dioxide
CORDEX	Coordinated Regional Climate Downscaling Experiment
CGIAR	Consultative Group on International Agricultural Research
CMIP3	Coupled Model Inter-Comparison Project 3
CMIP5	Coupled Model Inter-Comparison Project 5
CSAG	Climate Systems Analysis Group
DfID	Department for International Development
ECHAM5	Fifth-generation atmospheric general circulation model
EIA	Environmental Impact Assessment
ENSO	El Niño Southern Oscillation
ERA	European Centre for Medium-Range Weather Forecasts Re-Analysis
ERAINT	ERA-Interim
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization of the United Nations Statistics Division
FGD	Focused Group Discussion
GCM	General Circulation Model
GDP	Gross Domestic Product
GFCS	Global Framework for Climate Services
GHG	Green House Gases
GIS	Geographic Information System (s)
GoK	Government of Kenya
GPCC	Global Precipitation Climate Centre

ICPAC	Inter-Governmental Authority on Development (IGAD) Climate Prediction and Applications Centre
IDRC	International Development Research Centre
IFPRI	International Food Policy Research Institute
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change of the United Nations
ITCZ	Inter-Tropical Convergence Zone
KALRO	Kenya Agriculture and Livestock Research Organization
KMD	Kenya Meteorological Department
MALF	Ministry of Agriculture, Livestock and Fisheries
MAM	March April May
MDGs	Millennium Development Goals
NAPA	National Adaptation Programme of Action
NCAR	National Center for Atmospheric Research
NGO	Nongovernmental organization
OND	October November December
PRECIS	Providing REgional Climates for Impacts Studies
RegCM3	Third Regional Climate Model
REMO	REgional MOdel
RCMs	Regional Climate Models
RCP	Representative Concentration Pathways
SRES	Special Report on Emissions Scenarios (of the IPCC)
SSA	Sub-Saharan Africa
SST	Sea Surface Temperature
START	Global change SysTem for Analysis, Research and Training
TARDA	Tana and Athi Regional Development Authority
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WCRP	World Climate Research Programme
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting Model

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background information

Climate change is considered one of the greatest threats facing the world in the 21st century and there is vast scientific evidence that anthropogenic greenhouse gas (GHG) emissions are largely responsible (IPCC, 2007; Daron and Stainforth, 2013). Developing countries especially from Africa, arid and semi-arid lands (ASALs) in Africa and the resource poor in society are highly vulnerable to adverse impacts of climate variability and change (Cooper *et al.*, 2013). The impacts of climate change on environment, economy and social stability are diverse and concerted multi-institutional efforts are necessary to adapt and mitigate the effects (ACIA, 2004). Some of the key economic sectors that have experienced significant climate change related impacts in the last decade include agriculture, water resources, forestry, fisheries, biodiversity, human settlement, health and tourism (Thornton *et al.*, 2006; GoK, 2010b; Christensen *et al.*, 2007). In most of the developing countries such as Kenya, agricultural production remains a key driver for achieving development, poverty reduction and food security (World Bank, 2007; Nyasimi *et al.*, 2013). The majority of the local communities in the developing world depend mainly on crop production and pastoralism for their livelihood and employment (Salami *et al.*, 2010). However, climate change is exerting multiple stresses on the biophysical, social and institutional environments that underpin this agricultural production. The sector therefore remains highly prone to climate related risks and uncertainties of diverse magnitudes either in intensity, scope or frequency (Gornall *et al.*, 2010). Further, it is expected that climate change will modify the potential risks, vulnerabilities and other conditions that shape the resilience of future agricultural production systems while at the same time introducing new uncertainties.

Decision makers especially at regional and local levels need to understand climate change and its impacts so as to develop effective adaptation and mitigation measures. Principally, all climate change impacts and adaptation studies rely on information generated from climate models (Salath'e, 2005). However, a key limitation of using global climate models (GCMs) is the coarse horizontal resolution information that does not provide a representative description of local scale climate characteristics which are critical for practical resource planning (Wilby and

Wigley, 1997). Regional climate models (RCMs) are increasingly being used to provide in-depth understanding of the regional climate system processes including the projected future scenarios. The objective is to support policy development and planning processes such as the impact and adaptation studies being implemented at local scales (Fowler *et al.*, 2007). The downscaled climate information provides realistic and more specific descriptions of the climate system variables especially at local scales (Boulard *et al.*, 2012; Nikulin *et al.*, 2012). Kenya's arid and semi arid regions (such as the Tana River County) which rely heavily on climate sensitive natural resources as livelihood sources, requires such detailed climate information mainstreamed into policies, projects and other institutional activities being implemented. A number of RCMs such as those from the Coordinated Regional Climate Downscaling Experiment (CORDEX) have been developed to help understand regional climate dynamics (Wilby and Harris, 2006; Endris *et al.*, 2013) and quantify how climatic changes including the potential risks may occur in future.

This study was, therefore, designed to investigate the characteristics of rainfall, temperature and their interactions with crop and livestock productions in the Tana River County. The evaluations of these climatic variables were carried out at a range of time scales consisting of seasonal and annual cycles against weather station observational datasets. CORDEX RCMs were also used to simulate the Tana River County seasonal and annual rainfall characteristics. Their precision in simulating the observed climatic conditions enhances the RCMs confidence in projecting future rainfall and temperature characteristics. The study also examined the region's future agricultural production potential in the wake of climate change and variability. The study findings provide a basis for effective regional planning and policy development especially with regard to planned agricultural adaptation interventions.

1.2 Statement of the problem

Climate change and variability are among key challenges facing the society especially in the ASALs of Africa where natural resources are highly susceptible to climatic shocks. This vulnerability in ASALs is further exacerbated by long-term political and economic marginalization from mainstream development priorities, entrenched poverty and low levels of human development, high population migration, resource-based conflicts and environmental degradation. Kenya's agricultural production is largely rainfed and linked to seasonal and spatial rainfall distribution. Rainfall and temperature constitute key limiting factors of agricultural production and other livelihood sources in the ASALs of Kenya. Climatic information at regional and local scales is required by policy makers, natural resource managers, farmers and other development agencies to support their decisions. Farmers and policy-makers are apprehensive on the future projections of climatic information including understanding the potential impacts of climate on agricultural yields, food security and community vulnerability. However, climate change and variability information including long term data at local scale such as Tana River County is inadequate for decision making, planning agricultural activities, impact studies, adaptation mainstreaming or risk management. This inadequacy of climate related information has led to increased food insecurity due to poor strategies put in place, low mainstreaming of adaptation/mitigation measures, poor resource allocation and prioritization, and increased community vulnerability to climate related shocks. Decision making especially in the agricultural sector which is highly vulnerable to climate change and variability is constrained by limited climate information since the climate system is not directly under control of man. It is prudent to synchronize climate variability with agricultural production activities in order to minimize agricultural production risks and optimize agricultural production. It is in this context that research efforts are focused on the provision of downscaled climate data. The spatial domain of interest in downscaling climatic information is Tana River County, which has important socioeconomic and ecological functions to coast and northern Kenya ecosystem. The Tana River flood plain and delta is relied upon by farmers and nomadic pastoralists during the extreme droughts for water and green pastures.

1.3 Objectives of the study

1.3.1 Broad objective

The overall objective of this study was to downscale climate change information using regional climate models for agricultural planning.

1.3.2 Specific objectives

- i. To evaluate the performance of CORDEX RCMs in simulating rainfall and temperature characteristics in Tana River County
- ii. To evaluate the impact of rainfall and temperature on the agricultural production of Tana River County
- iii. To project future rainfall and temperature changes in Tana River County and their implications on agricultural production and related land resources

1.4 Research hypotheses

H_{0i} CORDEX RCMs do not accurately simulate the observed rainfall and temperature conditions in Tana River County

H_{0ii} There is no statistically significant relationship between rainfall and temperature characteristics and agricultural production in Tana River County

H_{0iii} Future rainfall and temperature in Tana River County would not adequately support agriculture and related land resources

1.5 Justification of the study

Tana River County has important socio economic and ecological functions to coast and northern Kenya ASALs ecosystem. River Tana, one of Kenya's largest and most important freshwater wetland supports farmers and nomadic pastoralists in the region particularly during extreme droughts. Therefore, the County is an important grazing zone for local and regional pastoral communities coming as far as Somalia, thereby, exemplifying its strategic importance in the region. The River flood plains and delta characterized by evergreen pastures and an abundance of river water, often receive additional influx of livestock during the period leading to over grazing and strong competition for natural resources. As a result, these grazing zones have increased the degradation of River Tana water resource (quality and quantity), increased community conflicts due to resource competition between farmers and pastoralists such as the

devastating 2012/13 Pokomo-Orma clashes (Manji, 2012), increased massive overgrazing and enhanced diversion of River Tana channel (see Plate 2). During the extreme drought periods, sedentary farmers (particularly the Pokomo sub-tribe) concentrate their crop production activities along the river flood plain supplementing their crops with River Tana waters while the pastoralists (mainly Wardei and Orma sub-tribes) concentrate their grazing activities along the same flood plains in search of green pastures and water for their livestock. This resource utilization pressure and competition along River Tana between the pastoralists and farmers is linked to the recurrent ethnic conflicts in the region. Over time, the County has experienced other significant climate induced risks such as the decreased water volumes and diversion of River Tana channel that have affected community livelihoods downstream triggering further conflicts.

The provision of downscaled climate information for the region to support understanding climatic trends (past and future) is one of the critical pillars to sustainable resource planning and management in the region. The downscaled climate information provides a data base to support decisions for adapting rainfed agricultural production and other climate risk management strategies. This downscaled climate information consists of climate change and variability, current and projected climate scenarios and potential agricultural risks linked to climatic changes. The Intergovernmental panel on Climate Change (IPCC) assessments reports have showed that the developing countries, marginal rainfall areas such as the Tana River County and resource poor in society are highly vulnerable to the current and projected future impacts of climate change and variability due to their low adaptive capacities (IPCC, 2007).

Tana River County relies heavily on climate sensitive livelihoods (such as rain-fed agriculture) and has experienced extreme climatic weather events (droughts and floods) that threaten the natural resilience of communities, thereby risking lives and livelihoods (Settele *et al.*, 2014). These climate induced risks have the potential of rendering this region effectively unproductive and uninhabitable (Omondi *et al.*, 2009). Therefore, there is need for downscaled climate information (such as rainfall and temperature) to support agricultural production, impact and adaptation studies in the region. The rainfall characteristics for the Africa region have been evaluated using RCMs (Meehl *et al.*, 2007) at a range of time scales such as seasonal, annual and diurnal cycles. However, there is need to connect these regional scale information including projections with local scale dynamics (such as Tana River County) to generate locally specific climate information for decision makers. Hence, the need for this downscaling approaches to

bridge the spatial scale gap for incorporation into decision making processes. The downscaled climate information along with their future uncertainties should then be clearly communicated to end-users and policy-makers so that robust decisions are made to respond to climate change and variability impacts (Weaver *et al.*, 2013).

1.6 Scope of the study

The study evaluated CORDEX RCMs in Tana River County to generate downscaled climate information for planning agricultural production. The RCMs were dynamically and statistically downscaled at 50km spatial resolution. The choice of CORDEX RCMs against other RCMs was guided by World Climate Research Programme (WCRP) recommendations on global climate downscaling beyond IPCC AR5, latest GCMs used in simulations (CIMP5), model performance in capturing regional features and model validation findings in Africa. The RCMs assessment/projection baseline period was taken from 1971 to 2000 (30 years). CORDEX RCMs data are available from 1989 to 2008 period. Field data collected from Tana River County comprised of climate and agricultural production datasets. Agricultural data sets consisted of crops and livestock records from Tana River County and were sourced from Tana River County sub-counties namely Tana North, Tana River and Tana Delta. Crop data sets comprised of the commonly grown crop types under rainfed conditions and their yields, while livestock data sets were livestock types and their population. The five crop types selected were maize, green grams, cassava, mangoes and rice. The relationship between agricultural production and CORDEX RCMs were limited to 20 years (1989-2009), the period which CORDEX RCMs data were available. Climate data set was limited to rainfall and temperature due to their significance to rainfed agricultural yields, productivity and other livelihood sources. The data was obtained from six weather stations located in Tana River County namely Garissa, Bura, Tana, Garsen, Witu and Kipini. Long-term climate data periods were used to understand climate characteristic of Tana River County. Finally, at least two Focused group discussions (FDGs) were employed to generate qualitative data regarding farmers' perceptions on the changing climate and their impacts on livelihoods. Focused Group Discussions (FGDs) and personal interviews were limited to representatives of village elders/headmen, chiefs, opinion leaders, clergymen, professionals and lead farmers.

1.7 Study limitations and assumptions

1.7.1 Study limitations

- i. *Availability of long-term climate data for the study area:* Tana River County as one of the ASAL areas had few weather stations and poorly distributed (Garissa, Bura, Tana, Witu, Kipini and Garsen). The existence of human and infrastructural challenges limited the data recording (including archiving) of long term weather records. Five weather stations (Bura, Tana, Garsen, Witu, Kipini and Witu) were rainfall stations and limited temperature analysis in the areas. Garissa station, the only synoptic weather station in the region was used to support major analysis for the vast region. Generally, less than 10% data gaps were found and filled using neighbouring weather stations data (Lamu, Masalani and Malindi) through interpolations.
- ii. *Distribution of weather stations in Tana River County:* The study found the spatial distribution of weather stations in the County was biased. Majority of weather stations were located along the River Tana channel leaving out the hinterlands areas. This distribution limited in-depth understanding of climatic trends along the hinterland areas largely occupied by the pastoralists. The study used neighbouring weather stations, data interpolation and satellite data to enhance such understanding in the region.
- iii. *Availability and accessibility of long-term agricultural data:* ASALs such as Tana River County were found to have challenges relating to data documentation, storage and reproduction linked to human and infrastructural deficiencies. There was a dearth of long term agricultural production data records of beyond 30 years. This limited long-term analysis and understanding to support agricultural adaptation and policy strategies in the region. The study's approach of working with committed and sub-county based agricultural extension officers enhanced the required data retrieval for the study.
- iv. *Topographic terrain and climatic conditions in the study region:* Although the region's ASAL conditions coupled with high insecurity limited movements during field data collections, all planned study operations were effectively executed due to effective planning meetings done at the beginning of the study. However, the conditions slightly affected the timing of some study visits resulting to some delays in data collection exercise.

- v. *Dynamical and statistical downscaling approaches:* The study acknowledged the specific merits and limitations of the two important climate information downscaling techniques as illustrated in Appendix 1. Therefore, the study used both techniques in addressing the objectives of the study.

1.7.2 Study assumptions

- i. *Determinants of agricultural yields.* Although the study assumed rainfall and temperature as key determinants of agricultural yields, the study found other factors such as culture, type and availability of seeds, time of planting and extension services need to be considered for successful increase in agricultural yields.
- ii. *Availability and accessibility of CORDEX RCMs data.* Although other types of RCMs exist such as PRECIS existed for simulation, CORDEX RCMs were preferred and used because they are the current internationally coordinated approaches for downscaling. CORDEX RCMs were assessed easily through the Inter-Governmental Authority on Development (IGAD) Climate Prediction and Applications Centre (ICPAC).
- iii. *Decreased livestock numbers.* The study assumed that declines in livestock numbers are largely associated with occurrences of climatic events mainly drought and floods. However, the study found that other factors such as high prevalence of diseases and inadequate livestock management skills contributed to increased livestock mortality.
- iv. *Farm management practices for agricultural production enterprises.* The study assumed that all farm management practices were appropriately and timely done by the farmers to achieve and sustain increased yields. However, the prevailing farmers' socio-economic conditions such as high poverty levels limit much of their intended operations.
- v. *Cultural barriers.* The study assumed the absence of serious cultural barriers such as religion that could hinder field work activities. Although there existed rich cultural diversity and entrenched cultural beliefs, taboos and norms in various communities in Tana River County, use of village headmen and local administrative officers provided the necessary breakthroughs to execute planned field work activities. Review of community background information from previous conducted studies in the region also provided baselines and frameworks for successful field visits.

1.8 Definition and operationalization of terms

In this study, the following many terms are used in the context of the research subject area and climate change perspective. These terms are as follows;

Agricultural production: The occupation of cultivating land, growing of crops (annual and perennial) under rain-fed conditions and keeping of livestock as a source of livelihood (Thornton *et al.*, 2010).

Climate: Long-term average of a given climatic statistics, often over time periods of 20 to 30 years (Nikulin *et al.*, 2012).

Climate change: Change in the state of the climate that can be identified (using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically a decade or longer (IPCC AR5, 2012). Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use.

Climate forcing: Are internal and external factors that influence the climate system and includes volcanic eruptions, solar variations, human-induced greenhouse emissions amongst others (Kendon *et al.*, 2010).

Climate information: Are summary statistics, time-series records, near-real-time monitoring, predictive information from daily weather to seasonal to inter-annual time scales, and the climate change scenarios required for decision making processes (IPCC, 2012).

Climate variability: Variations in the mean state and other statistics (standard deviations, the occurrence of extremes) of the climate on all temporal and spatial scales beyond the individual weather events (IPCC, 2007).

Coordinated Regional Climate Downscaling Experiment (CORDEX): A framework established by WCRP to produce regional climate change scenarios globally, contributing to the IPCC AR5 and climate community beyond the AR5 (Taylor, 2009).

Crop yield: The quantity of harvested crop product (cereal, grain or legume) from a crop area expressed either as kilograms (kg) or metric tons (t) of product per hectare (ha). Mathematically, Crop yield = (amount of harvested product) / (crop area) (World Bank, 2010).

Domain: A standard name assigned to each of the CORDEX area or region for downscaling (Giorgi *et al.*, 2009).

Downscaling: A set of techniques for generating local to regional-scale information from larger-scale modeled or observed data (Hewitson and Crane, 2006; Giorgi *et al.*, 2009). There are two main approaches: dynamical downscaling and statistical downscaling.

Ensemble: An average output of models used for climate projections (IPCC, 2012). The variation of the outputs across the ensemble members gives an estimate of uncertainty. Ensembles made with the same model but different initial conditions only characterize the uncertainty associated with internal climate variability, whereas multi-model ensembles including simulations by several models also include the impact of model differences.

Forecasts: Outputs that enable some level of confidence to be attached to projections. When a projection is branded “*most likely*” it becomes a forecast or prediction (Parson *et al.*, 2007).

General Circulation Models (GCMs): These are models that use numerical weather prediction equations to simulate changes associated with atmospheric and oceanic boundary layer conditions for the purposes of simulating climate variability and change (Hewitson and Crane, 1996). These models are coarse in resolutions and more useful on a global scale.

Grid cell: A rectangular area (box) that represents a portion of the Earth’s surface (Jones and Thornton, 2013). A grid cell contains climate-related physical information about that individual location.

Impacts: The effects on natural and human systems from the physical events, disasters and climate change (IPCC, 2012).

Indian Ocean Dipole (IOD): Are large-scale inter-annual variability of sea surface temperature (SST) in the Indian Ocean (IPCC, 2012).

Inter-annual variability: Year-to year change in the mean state of the climate that is caused by a variety of factors and interactions within the climate system (Jones *et al.*, 2013). One important example of inter-annual variability is the quasi-periodic change of atmospheric and oceanic circulation patterns in the Tropical Pacific region, collectively known as El Niño-Southern Oscillation (ENSO).

Large-scale climate information: Atmospheric characteristics (such as temperature, precipitation, relative humidity) spanning several hundred to several thousand kilometers (Benestad, 2007)

Lateral boundaries: Information about the air masses, obtained from GCM output or observations, used by RCMs to derive fine-scale information (Nikulin *et al.*, 2012).

Livestock mortality: Losses caused by the death of animals either through natural causes or illness attributed to droughts. Therefore, Mortality rate is a measure of the number of deaths (in general or due to a specific cause) in a population per unit of time. Mortality rate is typically expressed in units of deaths per 1000 individuals per year (Erenstein *et al.*, 2007).

Mitigation (of climate change): Human interventions to reduce the sources or enhance the sinks of greenhouse gases (IPCC, 2012).

Model: Algorithms and equations used to capture the behavior of a system being modeled (Van der and Mitchell (Eds.), 2009). Models serve to substitute reality for a range of scenarios.

Parameterization (climate models): Techniques of representing processes that cannot be explicitly resolved at the spatial or temporal resolution of the model (sub-grid scale processes) by relationships between model-resolved larger-scale flow and the area- or time-averaged effect of such sub-grid scale processes (IPCC, 2012).

Prediction: Statement about what something believes will happen in the future with no specific estimation (Parson *et al.*, 2007).

Predictand: The variable that is to be predicted. In downscaling, the predictand is the local climate variable of interest (Anandhi, 2009).

Predictor: A variable that can be used to predict the value of another variable. In downscaling, the predictor is the large - scale climate variable (Anandhi, 2009).

Projection (climate): An estimate of the rate or amount of something in the future computed with the aid of a model. It involves key assumptions; for example future socioeconomic and technological developments that may or may not be realized, and are therefore subject to substantial uncertainty (Parson *et al.*, 2007).

Radiative forcing: This is the change in the net, downward minus upward irradiance (expressed in W m^{-2}) at the tropopause or top of atmosphere due to a change in an external driver of climate change (Capotondi *et al.*, 2013)

Reanalysis: Are atmospheric and oceanic analyses of temperature, wind, current, and other meteorological and oceanographic quantities, created by processing past meteorological and oceanographic data using fixed state-of-the-art weather forecasting models and data assimilation techniques (IPCC, 2012).

Regional Climate Models: High-resolution (typically 50 kilometers) computer model that accounts for the local features such as topographical features and land cover in-homogeneity

(Fowler *et al.*, 2007). It is constructed for limited areas, run for periods of ~20 years, and driven by large-scale data.

Resolution: The quality of detail within an image or other spatial dataset. Therefore, spatial resolution refers to the fineness of the spatial detail visible in an image or land surface area contained within a pixel (New *et al.*, 2002).

Scale (spatial and temporal): Used to indicate the geographical coverage and is classified as local, national, regional and global. Where local/national represents a small geographical area (under 100,000 km²), regional represents sub-continental/continental region with many countries such as the East Africa region (100,000 to 10 million km²), while continental/global (10 to 100 million km²) is information representation of all countries of the world (Jones *et al.*, 2011). Temporal scales may be anywhere between seasonal to geological (up to hundreds of millions of years).

Scenarios (Climate): Are plausible and often simplified description of how the future climate may develop based on a coherent and internally consistent set of assumptions about key driving forces and climatological relationships (Zurek and Henrichs, 2007). They are storylines or images of how the future can unfold. Climate projection often serve as the raw material for constructing climate scenario, but climate scenarios usually require additional information such as the observed current climate.

Simulation: it is the actual running of a program (model) which contains equations or algorithm to generate a real-world process/system over time. The model represents the system itself (in this study CORDEX models), whereas the simulation represents the operation of the system over time (Taylor *et al.*, 2012).

Synoptic: Refers to large-scale atmospheric characteristics spanning several hundred to several thousand kilometers (Jones and Thornton, 2013).

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

This chapter reviews literature on climate modeling and assessment of global and regional climate change with specific interest on regional climate models, CORDEX RCMs, climate downscaling approaches as applied in the agricultural sector, characterization of rainfall variability in the eastern Africa region as influenced by the large scale drivers of the climate system, agricultural productions under the changing climate focusing on rain fed agriculture and lastly, climate change projections for agricultural production in the region. The chapter describes the importance of CORDEX RCMs as compared to other RCMs, what has been done and knowledge gaps to be addressed by the study.

2.2 CORDEX RCMs and their application in climate downscaling

The present climate downscaling efforts is the Coordinated Regional Downscaling Experiment (CORDEX) framework under World Climate Research Program (WCRP) which uses state-of-the-art Coupled Model Inter-comparison Project phase 5 (CMIP5) GCMs for downscaling. Giorgi *et al.* (2009) described CORDEX as international coordinated program to develop an improved framework for global generation of regional-scale climate projections for impact assessment and adaptation studies within IPCC AR5 timeline and beyond. CORDEX provides global coordination of “Regional Climate Downscaling” for improved regional impact assessment and climate change adaptation for a wider community in key sectors. The CORDEX RCMs are simulated at 50 km grid spacing (0.44° resolution) to favor the engagement of wider community applications in line with the Global Framework for Climate Services (GFCS).

Globally, a number of downscaling studies have been conducted using CORDEX RCMs in various regions to explore the uncertainties associated with dynamical downscaling techniques; Europe (Christensen *et al.*, 2006), North America (Mearns *et al.*, 2009) and South America (Menéndez *et al.*, 2010). In India, five CORDEX south Asia RCMs were used to evaluate the monsoon season precipitation and air temperature for the period 1951-2005 (Amit *et al.*, 2015). The study found that none of the RCMs captured the observed rainfall and temperature regimes in India and recommended for further model improvements before being used in regional climate change impact assessments. This finding concurred with the results

reported in Mishra *et al.* (2014) on the assessment of 11 CORDEX –South Asia RCMs for monsoonal precipitation over the Himalayan region. In Northeast Brazil (NEB), Santos e Silva *et al.* (2013) utilized the Regional Climate Model (RegCM4) to simulate the precipitation during 1998 and 1999 autumn seasons. The study found that the model captures regional and inter-annual differences of the precipitation in NEB. Further, the model outputs showed improvements in predictions particularly in the intensity and spatial distribution of the rainfall, relative to the ERA Interim reanalysis dataset.

In Africa, most of the regions are highly vulnerable to climate change and variability owing to the multiple stresses and low adaptive capacities (Boko *et al.*, 2007; IPCC, 2007). The IPCC reports indicates that the region has suffered significant consequences of climate change and climate variability over the last century and the recurrence of adverse impacts have increased in the last 40 years. Mohino *et al.* (2011) reports that in the last 10 years, most climate assessments in the region besides the climate mean state have also concentrated on climatic changes such as trends, periodicity or decadal variability as well as attributions (Omondi *et al.*, 2012a and b, 2013b). Equally, Gillett *et al.* (2012) described that most climate trends in Africa are been studied using CMIP5 models and not the regional climate models, a research gap this study addresses. Many downscaling efforts and studies in the Africa using global and regional climate models have mainly focused on climate change projections and diagnostic analyses of climate dynamics, for example the use of regional climate models to investigate Sahelian drought in West Africa (Jenkins *et al.*, 2005; Giannini *et al.*, 2003; Herceg *et al.*, 2007). According to Girorgil *et al.* (2009), climate downscaling studies in the Africa need to focus on establishing a better understanding of general responses of regional climate over specific predictions of local impacts, which was the thrust of this study. Some of the past commonly used regional climate models in impact studies in Africa include the RegCM3 (Soliman *et al.*, 2009), CCLM (Rockel *et al.*, 2008), REMO (Paeth *et al.*, 2005), MM5 of Penn State University/NCAR (Grell *et al.*, 1994), and PRECIS (Providing Regional Climates for Impact Studies) of the Hadley Centre, UK (Tadross *et al.*, 2005).

In West Africa, Dosio *et al.* (2014) applied COSMO-CLM (CCLM) regional climate model over the CORDEX-Africa domain to reproduce the general characteristics of the African climate (such as seasonal distribution of temperature and precipitation, and West Africa monsoon climatology) and compared the results with the simulations of four CMIP5 GCMs

(Max Planck Institute for Meteorology Earth-System Model running on low resolution grid [MPI-ESM-LR], Hadley Global Environment Model 2 - Earth System [HadGEM2-ES], Centre National de Recherches Météorologiques – Groupe d'études de l'Atmosphère Météorologique [CNRM-CM5], and European Centre Earth model [EC-Earth]). The study found that CCLM model had better representation of the annual precipitation. Further, by performing a singular spectrum analysis, CCLM reproduced satisfactorily the annual and sub-annual principal components of the precipitation time series over the Guinea Gulf, whereas the GCMs were not able to simulate the bimodal precipitation distribution due to the passage of the West Africa monsoon (WAM) but rather showed a unimodal annual cycle. Similarly, CCLM was able to better reproduce the probability distribution function of precipitation and some impact-relevant indices such as the number of consecutive wet and dry days, and the frequency of heavy rain events which are all critical in agricultural planning and production. Similarly, Sylla *et al.* (2009) assessed the ability of regional climate model (RegCM3) to reproduce the seasonal temperature and precipitation cycle during the period of 1981–2000 over West Africa region with two sets of boundaries conditions, reanalysis data and the fifth-generation atmospheric general circulation model (ECHAM5) output. In the same region, Akinsanola *et al.* (2015) applied three CORDEX RCMs to simulate the characteristics of rainfall pattern during the West Africa Summer Monsoon (1998 to 2008) in Guinea Coast, Savannah, and Sahel sub regions. The study found that the RCMs had ability to capture the African Easterly Jet (AEJ) and Tropical Easterly Jet (TEJ) with little variations in their position and intensity. However, it found significant biases in the individual models depending on the sub-region/location and season under consideration. These model biases were attributed to the strong cyclonic circulation observed at 850mb pressure level. The findings of these studies revealed that CORDEX RCMs can be used for the assessment of West African Summer Monsoon and their future climate projections. In South Africa (SA), Boulard *et al.* (2012) examined how the Weather Research and Forecasting (WRF) model accurately downscaled the ENSO-associated variability over the region when driven laterally by global re-analyses containing realistic ENSO signal. The study showed a limited skill of the WRF model to reproduce the seasonal droughts associated with the El Niño conditions.

In the eastern Africa region, downscaling studies conducted on rainfall cycles using Coupled Model Inter-Comparison Project phase 3 (CMIP3) and Coupled Model Inter-Comparison Project phase 5 (CMIP5) (Anyah and Qiu, 2012, Yang *et al.*, 2014) demonstrated

that GCMs either overestimate or underestimate the peak rainfall season of eastern Africa region with both models tending to shift the peak of the long rains season (MAM) and overestimate the short rains season (OND). A study conducted in Uganda by Nandozi *et al.* (2012) using PRECIS to simulate rainfall and temperature characteristics over Uganda and their likely future impacts when forced by an ensemble of two GCMs for the period 2070-2100 found that PRECIS captures fairly well the large scale flow signals influencing rainfall and temperature patterns over Uganda. It further indicated that rainfall and temperature patterns of the region were better resolved using RCMs than the GCMs. Another study by Endris *et al.* (2013) using CORDEX RCMs to simulate the characteristics of rainfall patterns over eastern Africa region and also the large-scale global climate forcing signals found that most of the RCMs reasonably simulate the main features of the rainfall climatology over the three sub-regions and reproduce majority of the documented regional responses to ENSO and IOD forcings.

In Kenya, Anyah and Semazzi (2006) applied regional model RegCM3 to analyze climate change characteristic under A2 emission scenario with a domain resolution of 20 km. The model was forced by global fields from the Finite Volume General Circulation Model (FvGCM). The study revealed that the average annual temperature was likely to rise between 1°C and 4°C by 2020 and 2100 respectively. Further, the regional climate was likely to be wetter in both rainy seasons but preferably during the short rain season (OND) and this further concurs with the findings of Shongwe *et al.* (2009). The study demonstrated that rainfall events during the wet seasons will become more extreme by 2100 while the flood events are likely to increase in frequency and severity. Equally, the application of GCM in the same region projects that only rainfall increases was likely to be observed in the northern Kenya (up to 40% by the end of the century) but the regional model suggests more detailed information of the likely greater rainfall in the west region of Kenya. Further, the findings indicate that rainfall seasonality (i.e. Short and Long Rains) were likely to remain the same. However, droughts in the region were likely to occur with similar frequency as at present, but with increase in severity that is linked to the increase in temperature. Another study by Okoth (2011) using PRECIS Regional Climate Model to study the potential response of Kenya's tea production in Kericho County to climate change found that PRECIS to large extent captured the rainfall and temperature characteristics of Kericho and was suitable for projecting future climate scenarios of the area. However, the study indicated that the model overestimate the minimum temperature.

The above review in the application of models for reproducing the current climatic observation and projecting the future climatic characteristics lies on the use of CORDEX RCMs, which this study endeavored to address. Kenya's economic development largely depends on agriculture and the application of CORDEX RCMs with specific focus on agricultural production makes significant contribution to decision making processes of addressing the potential future impacts of climate change and variability on the sector. The study findings envisage to guide planning and implementation of future adaptation strategies implemented in the agricultural sector. This research gap on application of CORDEX RCMs at sub-regional levels such as Tana River County formed the basis of this research which focuses on rainfall and temperature characteristics, very critical for planning agricultural activities.

2.3 Climate downscaling techniques in the agricultural sector

Edstrom *et al.* (2015) pointed out that understanding how climate of regions changes in the future under the forcing of greenhouse gases and aerosols is achieved through climate models (GCMs and RCMs). According to Daron and Stainforth (2013), climate models provides useful information and the means of understanding the range of plausible climate change conditions for meteorological variables such as precipitation, temperature, pressure, humidity, solar radiation and wind under the interactions of earth and atmospheric processes. However, several studies (Meehl *et al.*, 2007; Tabor and Williams, 2010; Fowler *et al.*, 2007; Salathé *et al.*, 2005; Jones and Thornton, 2013) demonstrated the limitations of GCMs in terms of coarse resolution in assessing the potential impacts of climate change on scales below 100 km² that links important areas such as biodiversity, ecosystem services, agricultural systems, species distributions, conservation planning and other landscape and agriculture related matters. Wilby and Dawson (2013) reported the downscaling attempts to resolve models scale discrepancy between climate change scenarios provided by GCM models and the resolution required for impact assessments. The study illustrated that the downscaling processes are based on the assumption that large-scale weather conditions exhibits a strong influence on local-scale weather. The study suggested that applying downscaling techniques to such global information allows scientists to obtain regional projections of climatic changes useful for impact and adaptation studies.

The concept and products of downscaling have been tested widely in the last two decades by decision makers to solve climate-change related problems, making the downscaling tools important in climate change research (Platts *et al.*, 2015). Attempts have been made to address

the limitations of coarse spatial resolution experienced in global climate models through the downscaling process. It attempts to bridge the gap between global and local effects by layering local-level data over larger-scale climate models. The goal is to generate more locally relevant projections of long-term weather patterns for regions, states, and sub-regional levels. This spatial scale mismatch in modelling formed the basis for this study, utilizing both the dynamical and statistical techniques to generate regional/local scale climate information useful for decision makers planning agricultural activities in Tana River County.

Climate change is one of the greatest concerns in agricultural production as it impacts on food security (Parry *et al.*, 2007). According to Villegas and Challinor (2012), coupling climate downscaling with agricultural activities such as crop production processes helps examine the value of downscaling in the prediction systems. However, the assumptions underlying the individual model application along with potentials and limitations must be understood by the users (Bader *et al.*, 2008). Downscaling techniques in the agricultural sector are considered necessary for impact assessments because factors that affect crops such as soil, rainfall, temperature and farming practices vary at finer scales (Zhang, 2005). In response to the demand of downscaled (finer scale) climate change information for decision makers in the agricultural sector (Villegas *et al.*, 2013), a number of climate change downscaling studies using regional climate models have been carried out across the world (Mearns *et al.*, 2001 and Challinor *et al.*, 2009). Edstrom *et al.* (2015) described two downscaling techniques; statistical, dynamical and their combinations as the commonly used to produce finer scale information for the management of key agricultural activities such as crop varietal selection. Several studies (Maurer *et al.*, 2007; Wilby and Dawson, 2013) described the application of statistical downscaling approach to generate useful fine scale information. The approach used empirical relationships between large-scale atmospheric and local climate variables. Maraun *et al.* (2010) and Wang *et al.* (2015) emphasized the limitations hampering the application of statistical approach which includes lack of long-term observational data at point or station scales especially in the ASALs required to validate the statistical model. Equally, Schmidli *et al.* (2006) described the alternative dynamical downscaling technique which is computationally intensive and captures mesoscale nonlinear effects using high-resolution global models with variable spatial resolution. Similarly, this approach suffers from uncertainties inherited from the driving GCMs and from those associated

with model internal workings. This study utilized the combination of both statistical and dynamical downscaling approaches in addressing the study's objectives.

2.4 Characterization of rainfall variability in the eastern Africa

In eastern Africa, both the large and local scale drivers of the climate system greatly influences rainfall variability with much of these variability occurring during the short rainy season of October – December (OND) and is linked to large-scale climate systems such as the El Niño Southern Oscillation (ENSO) (Mutai and Ward 2000, Indeje *et al.*, 2000) and the Indian Ocean Dipole (IOD) (Behera *et al.*, 2003; Black *et al.*, 2003; Black, 2004 ; Shreck and Semazzi, 2004; Behera *et al.*, 2005; Owiti *et al.*, 2008, Cai *et al.*, 2014). El Niño is the most important factor responsible for inter-annual variability of precipitation in the eastern Africa. Ogallo *et al.* (1988) found that the warm ENSO phase is associated with anomalously high rainfall events in East Africa while the cold phase is associated with drought. It is anticipated that the frequency, severity and extent of climate related risks such as floods and drought in the region will increase due to projected climatic changes (Hellmuth *et al.*, 2011; United Nations Economic Commission for Africa, 2011). Christy *et al.* (2009) reported that a significant feature in temperature variability patterns in the eastern Africa is the recurrence of extreme values that are significantly correlated with the patterns of convective activities such as cloudiness and above normal rainfall. Cai *et al.* (2014) using an ensemble of climate models forced by high greenhouse gas emissions scenarios, projected that the frequency of extreme positive IOD events will increase by a factor of three from the twentieth to the twenty-first century. These increasing modes of climate variability and associated extreme climatic events in the region will have serious impacts on the economies of eastern Africa countries and other community livelihoods considering the low adaptive capacities and high dependence on rain-fed agricultural systems (IPCC, 2014).

2.5 Agricultural production and changing change

Climate change is one of the major threats facing humanity in the 21st century and their effects in the agricultural sector is detrimental especially in the developing countries characterized by their low adaptive capacities and high dependency on climate sensitive resources (FAO, 2005; Müller *et al.*, 2011). The Sub-Saharan Africa (SSA) is the most vulnerable region to climate change since its agricultural productions is largely rainfed (Calzadilla *et al.*, 2013). According to Food and Agriculture Organization of the United Nations

Statistics Division (FAOSTAT, 2012), food security is the greatest challenge in Sub-Saharan Africa and the proportion of undernourished population is highest globally (approximately 30 percent). The vulnerability of the agricultural systems in Africa is further aggravated by the dominance of smallholder farmers having limited opportunities for investment in agricultural inputs required to enhance farm productivity; fertilizers, pesticides, mechanization and irrigation (Roudier *et al.*, 2011). The Commission for Africa Report (2005) highlighted that despite the climatic challenges facing the African continent, the agricultural sector is the backbone of economic development for most countries, supporting up to 80 percent employment and average of 30 percent Gross Domestic Product (GDP).

At the global scale, Asha latha *et al.* (2012) estimated that up to 80% of the total agricultural land is rainfed and generates 65 to 70 per cent of staple foods. Additionally, more than 95% of the total crop land area in the SSA is under rainfed system (FAO, 2005), thereby exposing the region's future agricultural production to high risks of seasonal rainfall variability (Calzadilla *et al.*, 2008). Cooper *et al.* (2008) reports the existence of additional challenges facing the agricultural productions in SSA such as the widespread poverty that limits agricultural expansions and the adaptive capacity. Therefore, against all these factors influencing agricultural production in the region, decision makers such as agricultural managers faces a major challenge of the inadequate climatic information that supports their day-to-day decisions on how to supply sufficient food for the rapidly increasing population under the changing climatic conditions while sustaining the already stressed environment resources (Department for International Development [DFID], 2005). The inadequacy of downscaled climate information is linked to the increasing food insecurity and community vulnerability to climate related shocks experienced in the region and thereby forms the thrust of this study.

The Intergovernmental Panel on Climate change Fourth Assessment Report (AR4) indicated that impacts of climate change on agricultural production are not geographically uniform and that regions such as the SSA are adversely impacted (IPCC, 2007). Several studies have also reported the impacts of both climate change and variability and extent of vulnerability in the agricultural production systems in the developing countries (Calzadilla *et al.*, 2008; Kalra *et al.*, 2007). Generally, there is a consensus that changes in temperature and precipitation is negatively impacting on crop growth, yields and their spatial distribution, thereby exerting more pressure on other community livelihood sources (Liwenga, 2008). The high vulnerability of the

agricultural sector to climate change and variability together with limited resources to implement appropriate adaptation measures is attributed to cause low and declining yields for most important staple food crops in the SSA (International Food Policy Research Institute [IFPRI], 2009), thereby leading to increased food insecurity and vulnerability to climate related shocks (Lal, 2005; Beddington, 2010). The Sustainable Development Goal two (SDG2) of the United Nations (UN) of “End hunger, achieve food security and improved nutrition and promote sustainable agriculture” by 2030 (UN, 2015; International Council for Science (ICSU)-International Social Science Council (ISSC), 2015) is a key challenge in the sub-Saharan Africa under the changing climatic conditions. Magombeyi *et al.* (2008) recommends that agricultural production systems particularly in the vulnerable regions incorporates climate resilient technologies/innovation, while the policy makers and planners in these sectors utilizes downscaling information and approaches to support decision making especially planning key agricultural adaptation measures (Popova and Kercheva, 2005). Cooper *et al.* (2008) further suggests that a comprehensive strategy for the agricultural sector is required if the considerably more complex challenge of adapting agriculture to future climate change is to bear fruit.

Several studies (Dinar *et al.*, 1998; Seo and Mendelsohn, 2008; Cline, 2007) have also shown significant effects of climatic changes (mean rainfall and temperature) on crop yields. In Sub-Saharan Africa, climate simulation models have shown that changes in the mean climate as well as increases in climate variability have significant effects on the region’s agricultural production (Thompson *et al.*, 2010 and Knox *et al.*, 2012). These observed climatic changes have not only decreased yields but also increased the risks and uncertainties in the food production systems (Reddy and Pachepsky, 2000). Under the IPCC emissions scenarios (2007), climate change will adversely impact the extent and productivity of both irrigated and rainfed agriculture in most parts of the world. Sanchez *et al.* (2009) reports that the main limiting constraint in the rainfed production systems under the changing climate is water availability for crop production with direct effects on yields and food security. Future projections shows that the reductions in rainfall and rising mean surface temperatures will lead to decreased water availability and increased water demand for crop production (IPCC, 2007).

In the eastern Africa, rainfall variability and change have adversely affected agricultural productions (Schreck and Semazzi, 2004; Kilembe *et al.*, 2013) and therefore the need for further studies targeting the management of future agricultural activities. The region is one of the most

food insecure and largely attributed to the frequent climate related risks (Slegers and Stroosnijder, 2008; Demeke *et al.*, 2011; Gray and Muller, 2012). The region's strong dependence on rainfed agriculture is described as a quasi-linear relationship between grain yields, seasonal rainfall and food deficits (Funk *et al.*, 2008). An earlier study by Funk *et al.* (2005) showed that warm sea surface temperatures are responsible for the recent droughts in equatorial and sub-tropical eastern Africa during the 1980s to the 2000s. According to the UN Food and Agriculture Organization (FAO, 2004), the number of African food crises per year tripled from the 1980s to 2000s. Drought diminished water supplies which reduced crop productivity and thereby led to widespread famine in eastern Africa. Hastenrath *et al.* (2007) found that eastern Africa has suffered both excessive and deficient rainfall and especially the increased frequency of anomalously strong rainfall causing floods. Shongwe *et al.* (2009) using data from the international Disaster Database (EM-DAT) showed the increase in the number of hydro-meteorological disasters in the region, from an average of less than 3 events per year in the 1980s to over 7 events per year in the 1990s and 10 events per year from 2000 to 2006, with a particular increase in floods. In the period between 2000 and 2006, these disasters affected on average almost two million people per year.

In Kenya, agriculture is the backbone of the economy contributing up to 25% of gross domestic product (GDP) as well as employing approximately 75% of the national labour force (Republic of Kenya, 2005; Alila and Atieno, 2006). The high reliance on rainfed agriculture that is highly vulnerable to weather variability has led to the frequent fluctuations in crop yields and incomes especially for the small-holder farmers (Thornton *et al.*, 2010). Several study reports (McSweeney *et al.*, 2009; Omumbo *et al.*, 2011; Mekasha *et al.*, 2014; Omondi *et al.*, 2013a) have shown the impacts of the changing trends in mean rainfall and temperature on the current and future agricultural productions. Moore *et al.* (2011) demonstrated the increased frequency and intensity of extreme climatic events such as droughts and floods in Kenya that causes crop failures, loss of livestock and food insecurity. This climate related challenges facing the agricultural sector in the country and especially in the ASALs can be addressed by among other interventions the provision of relevant finer scale climate information that supports the decision making processes. The inadequate region based climate information have significantly impacted the many agricultural decisions leading to the increased food insecurity and low mainstreaming of adaptation strategies in the sector. Provision of downscaled climate information allows the

synchronization of the various agricultural activities with climatic events, thereby enhancing the management of climate related risks. Therefore, this research aimed to address this particular knowledge gap in climate information with specific focus on Tana River County.

2.6 Climate change projections and agricultural production

The impact of climate change in the agricultural sector is of great concern to policymakers, development experts, and farmers (Tenge *et al.*, 2013). Agriculture and climate change are inextricably linked through crop yield, biodiversity, water use, as well as soil health which are all directly affected by the changing climate. Thompson *et al.* (2010) observes that developing countries whose economies are based on agriculture are already experiencing rising temperatures, unpredictable rainfall, and extreme climatic events that are endangering rural livelihoods as well as threatening national food security. The study further reports that crop production is expected to be reduced since the optimal growing temperatures are exceeded and growing seasons shortened due to the climatic changes. The areas appropriate for key crops are expected to shift as local climates change. Additionally, the study found that a warming exceeding a global mean temperature change of 3°C would imply that virtually all of the present crops such as maize, millet, and sorghum cropping areas across Africa could become unviable for current cultivars. A study undertaken by Kabubo-Mariara and Karanja (2007) in Kenya indicated that climate change causes 22 percent loss of crop production in medium and low potential ecological zones and 1 percent production gain in high potential zones. As a result of these current and potential impacts in the agricultural sector, Cooper *et al.* (2009) observed the need for adaptations of agricultural activities to the current and projected climatic changes, which may have policy implications both at the national and devolved government levels. The study recommended for increased application of downscaled climate information in the implementation of planned changes in processes, practices, or structures that will minimize the potential damages or take advantage of opportunities associated with climatic changes.

Plausible estimates of projected climate change impacts on agriculture can be achieved through combined use of climate, crop, and economic models (Rosenzweig *et al.*, 2013). Climate models support decision makers understand the projected climates and visualize the different impacts of the agricultural sector as influenced by climate patterns (Van Vuuren *et al.*, 2013). Several studies in the developing countries on the projected climates (GoK, 2010; Chambwera and Stage, 2010; Agrawala and Fankhauser, 2008; UNFFC, 2010; Thompson *et al.*, 2010)

demonstrated strong scientific evidence of the extreme and unpredictable climatic changes with expected negative impacts in the agricultural sector. The findings in these study reports have supported decision makers to confront the complex and difficult task of synchronizing planned agricultural activities with the projected climatic events. Kamau and Mwaura (2013) examined the extent to which climate change adaptation measures in Kenya has been integrated in the Environmental Impact Assessments (EIAs) studies and found that most previous studies had weak climate change projected scenarios which likely impacts on decision making regarding planned agricultural activities/projects being implemented.

Regional climate models (RCMs) have been applied to downscale climate scenarios to regional scales for climate change impact studies. Glotter *et al.* (2014) utilized dynamical downscaling approaches in projecting maize yield, one of the greatest concerns under climate change. Glotter *et al.* (2014) reported that that the benefits for impacts assessments of dynamically downscaling may not be sufficient to justify its computational demands. Further, Qian *et al.* (2015) used CERES-Wheat model in DSSAT to project changes in spring wheat yield on the Canadian Prairies (2041–2070), the model showed an average increase ranging from 26 to 37 % of the baseline yield and hence, its potential use in climate change impact assessment. Therefore, the studies found it interesting to investigate how RCMs projects the potential agricultural crop yield changes in various regions to support planning and adaptation mainstreaming initiatives. This study therefore applied CORDEX RCMs in projected the potential agricultural impacts of climate change in Tana River County.

CHAPTER THREE

3.0 METHODOLOGY

3.1 Introduction

This chapter describes the study area characteristics and the specific techniques used in data collection, management and analyses to achieve the results for the study specific objectives. The discussed study area characteristics include the physical location, population, livelihood sources, climate, soils, vegetation and biodiversity. The chapter also gives information on the research design adopted, types of data and collection approaches, data sources, sampling procedures used, data management, data reliability and validity, data statistical tools and analyses used.

3.2 The study area

3.2.1 *Physical location*

The study was carried out in Tana River County located in the former Coast province of Kenya. It lies between latitudes $00^{\circ}00'45''\text{S}$ to $03^{\circ}02'07''\text{S}$ and longitudes $38^{\circ}24'02''\text{S}$ to $40^{\circ}45'18''\text{S}$ as illustrated in Figure 1. It is located about 150km north of Malindi through the Malindi - Garsen B8 road and its capital town is Hola (also known as Galole). Tana River County covers a total surface area of $38,437\text{km}^2$ and accounts for 6.61 percent of Kenya's total surface area (Mireri *et al.*, 2008). The County is named after River Tana which is the longest river in Kenya covering up to 1000 kilometres in length. The County borders Garissa to the Northeast, Isiolo to the North, Lamu to the East, Kilifi and Taita Taveta to the South, and Kitui to the West (see Figure 1). Administratively, Tana River County consists of three Sub-counties namely Tana Delta, Tana River and Tana North (see Figure 1).

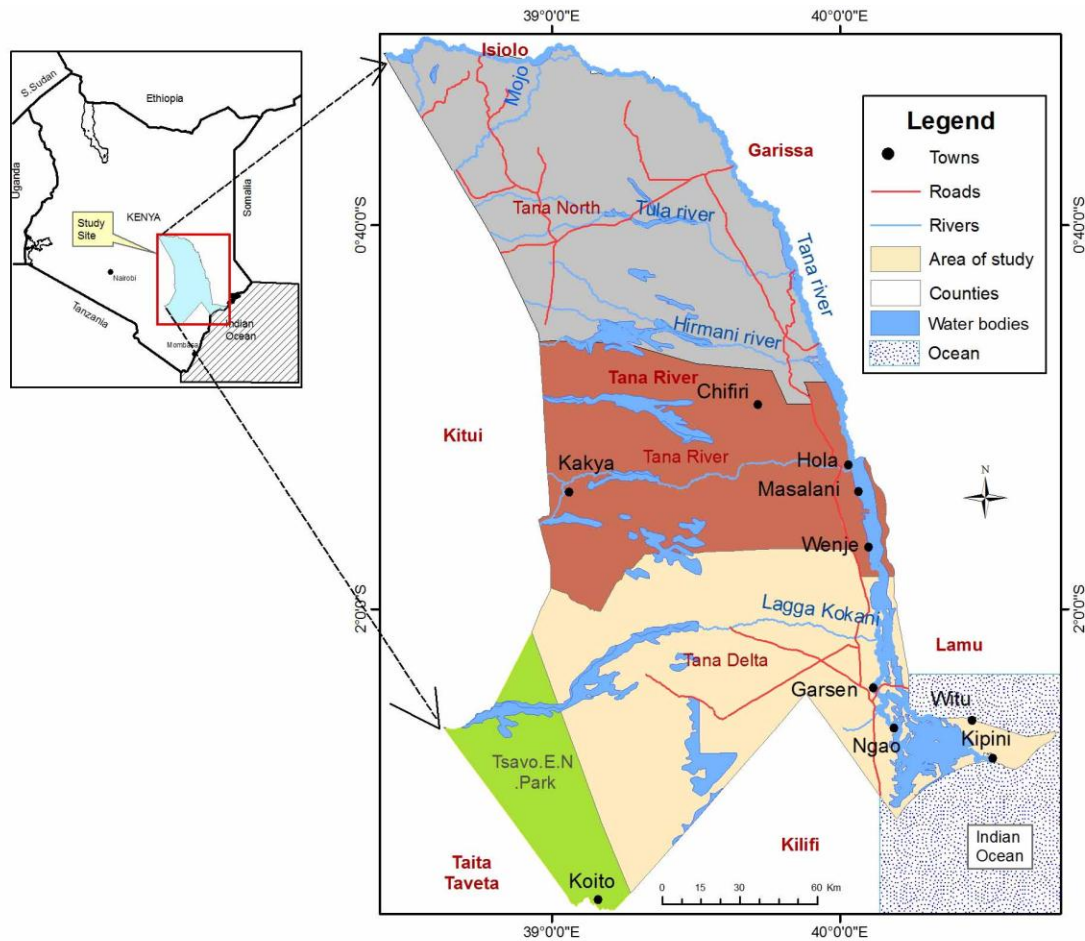


Figure 1: Map of Kenya showing the study area (*Source: Author, 2015*)

Although the study focused on Tana River County as an administrative unit, the area for climate information downscaling was designed in a rectangular grid box (pixel) to conform to the climate downscaling procedures. Thus, the downscaling area does not coincide with Kenya's Counties administrative boundaries specifically Tana River County. The downscaling pixel covering the study area (Tana River County) incorporated small sections of Garissa, Kilifi, Kitui, Isiolo and Lamu Counties as illustrated in Figure 1 above. These small sections from other Counties were insignificant to influence the downscaled outputs since no major localized forcings were captured in the grid cell (downscaling pixel).

River Tana channel has diverted its course at several points in the County and is widely linked to the impacts of climate change. Plate 1 below illustrates the diversion at Mnazini area in Garsen.



Plate 1: River Tana channel diversion at Mnazini area near Garsen town

3.2.2 Demographic characteristics and livelihood sources

According to 2009 population and housing census, Tana River County had a population of 240,075 and constituted 0.6 % of the national population (KNBS, 2009). This population is generally sparsely distributed in the County except along River Tana and urban centres with dense settlements. The County is largely characterized by a migratory population consisting of livestock herders (pastoralists) who migrate to the lower plains during the driest months of January and February. The major ethnic groups in the County are the Pokomo, Orma, Wardey, Somalis and Wasanye. There are also Luo and Luhya immigrants who are actively engaged in the thriving fishery sector.

Economically, Tana River County largely relies on livestock (pastoralism), crop production, fishery, tourism, bee-keeping and other biodiversity benefits for economic development (Maingi and Marsh, 2002). River Tana, a vital water resource in Tana River County supports many livelihood activities for majority of the population. The Pokomos are the main agriculturists growing crops under rainfed and along River Tana floodplains. They cultivate narrow strips on either side of the river and around the seasonal and permanent wetlands. The various crops grown in the County include mangoes, rice, maize, cassava, bananas, green grams, beans, peas, melons, cowpeas, pawpaw, tomatoes, kales, onions, cabbages, sugarcane, and

vegetables. These crops are produced for both household consumption and domestic markets (local and regional). The County is also well known for the production of the popular apple, mango and rice from Bura and Tana and Athi Regional Development Authority (TARDA) irrigation schemes.

Livestock production also constitutes a key livelihood activity in the County for both the pastoral and sedentary communities. The major livestock types kept include cattle, sheep, goats, camel and donkeys. The Orma and Wardey tribes are predominantly pastoralists and use the available wetlands, Tana delta and flood plains as dry-season grazing zones for their livestock. During the prolonged dry spells, many pastoral communities migrate into the area as far as Somalia in search of water and green pastures. This exemplifies the strategic importance of the region to local as well as the entire Coast and Northern Kenya ASAL communities. The lower Tana River is also known for the rich diversity of fish species. The FISHBASE website (www.fishbase.org) has listed 44 fish species found in the lower Tana River, most of which are found in the main river channels, particularly in sheltered, low water velocity areas, swamps and in the oxbow lakes, which provide unique spawning grounds for fish species. These fisheries resources (especially lung fish) provide important ecological functions not only to the coastal market but also to fish eating communities in Nairobi, Western and Nyanza provinces. Fishing is an important source of food, income and employment in the region.

3.2.3 River Tana basin

Tana River basin is one of the biggest river basins in Kenya consisting of the upper, middle and lower basins. The lower basin which covers Tana River and Garissa Counties is prone to frequent floods (see Figure 1). River Tana stretches over a total length of 1,000 km and flows most of its course across arid and semi-arid regions, meandering through an alluvial floodplain before entering into the Indian Ocean through Kipini (see Figure 1). The river forms Tana Delta, the largest deltaic ecosystem in Kenya that stretches over 180,000 km² (Terer, 2004). There are several tributaries feeding River Tana in the lower Tana basin such as Mojo, Tula, Hirmani and Legga Kokani (see Figure 1).

Generally, Tana River basin supports livelihoods for more than four million people most of whom are pastoralists, farmers and fishermen (Nyingi *et al.*, 2011). River Tana is the major source of water in the County for livestock, irrigation, domestic, industrial (power generation, tourism, and micro-enterprises within the basin) and recreational functions such as boat riding

and sport fishing (Maingi, and Marsh, 2002). Other sources of water in the County include seasonal rivers, ground water, water pans and water holes in the inter-laga areas (Table 1). There are several dams situated in the pastoralists grazing zones (far-away from River Tana) constructed by the Arid Lands and Drought Recovery and National Water Corporation for the watering of livestock. Adequate supply of good quality water is crucial for the vibrant livestock sector in the region. In some sections, River Tana is used for leisure canoeing but this is mainly combined with fishing. Therefore, River Tana as a resource is highly valued by Tana River County government and local communities as an important means of livelihood support to the whole of Tana River basin population.

Table 1: Sources of water and their proportions in Tana River County

Source	Proportion (%)
Tana River	63.9
Other Streams	1.7
Ponds/pans	11.0
Springs	0.3
Wells/ boreholes	18
Roof catchment	4
Unknown	0.9

(Source: Maingi and Marsh, 2002)

3.2.4 Climate

Tana River County is largely considered arid and semi-arid region having mean annual rainfall of between 200 to 500mm (Maingi and Marsh, 2006). However, some sections along the coastal strip (Such as Kipini) receive high mean annual rainfall of between 1,200 to 1,500mm. The rainfall pattern in the region is bimodal received during long rains of March to May (MAM) and sometimes extending to June and the short rains of October to December (OND) period. The mean annual temperature ranges between 27⁰C and 33⁰C. The average annual wind speed is about 2.5 m/s and varies during the different months from 1.7 m/s in December to 3.1 m/s in August. Generally, the climate of Tana River County is described as hot, dry and humid for most part of the year (IUCN, 2003).

In the tropics such as the eastern Africa and Tana River County, the climate system elements such as rainfall variability and distribution are generally controlled by the seasonal migration of the inter-tropical convergence zone (ITCZ) that migrates, north-south, across the region twice a year. The ITCZ imposes significant influence on the climatological rainfall and temperature patterns of the region. It influences and defines the bimodal rainfall regime experienced in most parts during March to May (MAM) and October to December (OND). Other climate systems influencing the region's climatology include the Indian Ocean Dipole (IOD) and El Niño–Southern Oscillation (ENSO). These large scale climate system drivers are associated to the extreme weather and climate events such as floods and droughts experienced in the eastern Africa region which causes huge socio-economic losses.

3.2.5 Vegetation and biodiversity

Tana River County has important natural resources and high biodiversity hotspots critical for the socio-economic development of its people. The County has high diversity of habitat types which includes riverine forests, grasslands, woodlands, bush lands, lakes (such as Lake Bilisa), open river channels, estuaries, sand dunes, mangroves and coastal waters (Moinde-Fockler *et al.*, 2007). This high diversity of habitat types in the region is associated with high biological diversity of both flora and fauna (Hamerlynck *et al.*, 2011). Tana River basin sustains large numbers of mammals, birds, reptiles, fish, amphibians, insects and galleries of riverine forests. The river floodplains and their associated mosaics of riverine forest patches is an important habitat for the threatened and endangered species such as the Tana River Red Columbus monkey, Tana River Crested Mangabey, elephants, fish and plants. The riverine wetlands in the region are important ecosystem that acts as a staging, resting, nesting and feeding ground for resident and migratory water birds. There are also important wildlife conservation areas of concern in the County such as the Kora, Arawale and Tana Primate National Reserves. These areas are of international conservation importance due to the unique biological diversity they harbour including the hunter's heartbeast (Hirola), Tana River Red Colobus monkey and the Tana River Crested Mangabey among others (Hamerlynck *et al.*, 2011).

3.2.6 Soils

The soils in Tana River County are diverse and consist of eutric and vertic Fluvisols, mollic Gerysols, ortho-luvic and vertic Luvisols (saline-sodic phase), gleyic Solonetz, chromic

Vertisols and ferrallo-chromic orthic Acrisols (sodic phase with Solodic Planosols). The summary characteristics of soils in Tana River County are shown in Table 2.

Table 2: Soil characteristics in Tana River County

Soil type	Description	Remarks
Eutric and vertic Fluvisols	Well drained, very deep and stratified cracking soils of varying color, consistence and texture, in places slightly calcareous and moderately sodic	Landform: river alluvial plains (slopes 0-2%) Parent material: recent alluvial deposits
Calcic Cambisols, sodic phase	Moderately well drained to imperfectly drained, very deep, brown, very firm, strongly calcareous, moderately sodic, sandy loam, to silty clay loam	Landform: plains of river terraces (slopes 0-2%) Parent material: lagoonal sands and clays
Eutric Gleysols Sage	Imperfectly drained, very deep, pinkish gray, mottled, friable, slit loam to clay	Landform: swamp Parent material: recent alluvial deposits
Complex of chromic Vertisols	Moderately well drained, very deep, brown, mottled, very firm, cracking silty clay	Landform: river alluvial plains
Eutric and vertic Fluvisols	Well drained to moderately well drained, very deep, stratified cracking soils of varying color, consistence and texture; in places moderately calcareous and sodic	Parent material: recent alluvial deposits
Ferralic Arenosols	Somewhat excessively drained to well drained, very deep, red, loose to friable, sand to sandy loam; in places slightly calcareous	
Chromic Vertisols	Moderately well drained to imperfectly drained, very deep, dark brown, mottled, very firm, cracking clay; in places slightly calcareous and moderately sodic	Landform: river alluvial plains Parent material: recent alluvial deposits

(Source: Lebrun et al., 2010)

3.3 Study research design

A single case study research design (George and Bennet, 2005) was adopted focusing on Tana River County representing one of Kenya's ASAL Counties and application of CORDEX regional climate models as "case and subject" respectively (Yin, 2009) to provide quantitative evidence on the performance of RCMs in simulating Tana River County climate characteristics (rainfall and temperature) to support decision making processes relating agricultural production activities,

climate change impact and adaptation studies (see Figure 2). Tana River County was selected considering that River Tana, a key resource in the region stretches over 1000 km, flows its course across arid and semi-arid regions, and meanders through the alluvial floodplain before entering into the Indian Ocean through Kipini. Further, the river forms Tana Delta, the largest deltaic ecosystem in Kenya that stretches over 180,000 km². Hence, Tana River basin supports livelihoods for majority of people most of whom are pastoralists, farmers and fishermen.

Multiple sources of data were employed in the study consisting of agricultural production, climate and RCMs to investigate Tana River County (the “case”) and address the study specific objectives. In downscaling Tana River County climate information, the performance of CORDEX RCMs forced by semi-observed ERA-Interim re-analysis was tested over eastern Africa to ensure it captures the regional patterns linked to ITCZ before being used to downscale climate information for Tana River County. A combination of both dynamical and statistical downscaling approaches was employed to cascade climate information into Tana River County (see Figure 2). This is because each downscaling approach has inherent limitations. The statistical approach is limited by lack of long-term observational data at point or station scales especially in the ASALs (such as Tana River County) required validate the statistical model. Equally, the dynamical downscaling technique is computationally intensive and captures mesoscale nonlinear effects using high-resolution global models with variable spatial resolution. This approach suffers from uncertainties inherited from the driving GCMs and from those associated with model internal workings.

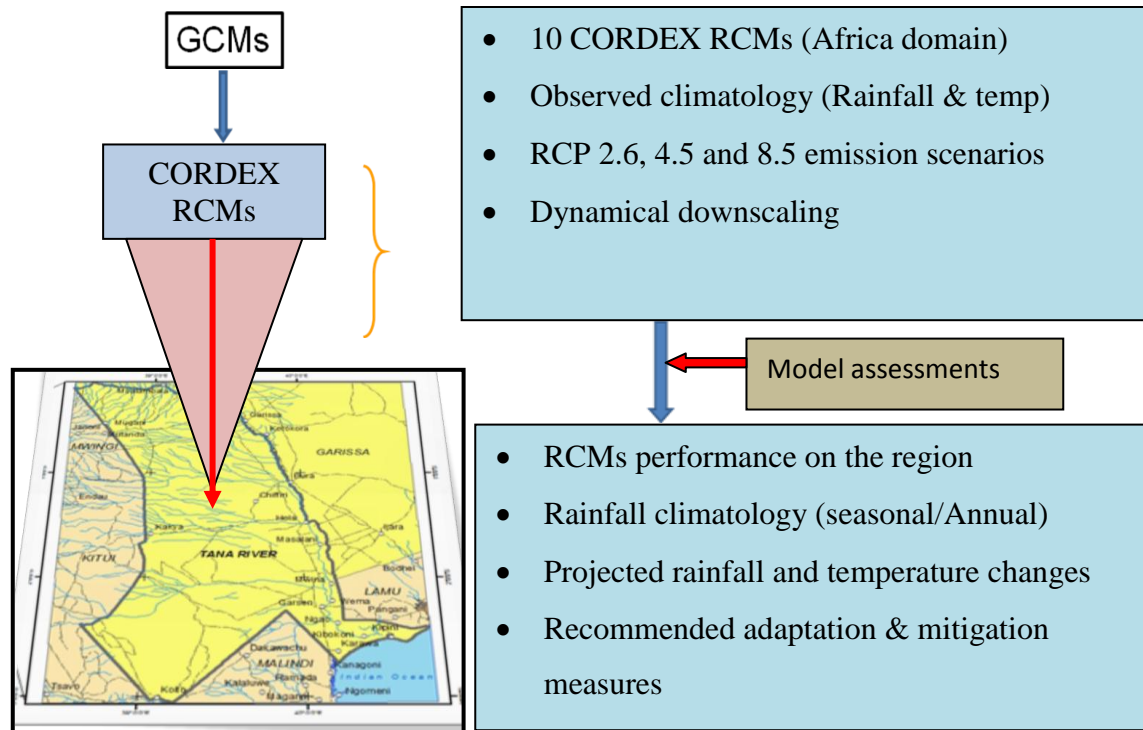


Figure 2: Research Design Framework (Source: Author, 2014)

3.3.1 Case study

The study utilized several systems of concepts, existing theories and assumption to address the broad and specific objectives set out in the research plan. The explored theories were based on climate research modeling focusing on GCMs and RCMs as tools of assessing the climatic changes resulting from natural and anthropogenic causes. The review of theories and concepts provided the research gap for this study relating downscaling climate change information for regional/local scale agricultural planning. Thematization field of study guided the selection of a case study area (Tana River County) for the application of the formulated research concept. Three sources of data was employed namely agricultural, climate and regional climate models (CORDEX) to investigate in-depth Tana River County as a case study and address the specific objectives. Figure 3 illustrates the schematic flow of research steps and the variable interactions involved for the research findings and conclusions.

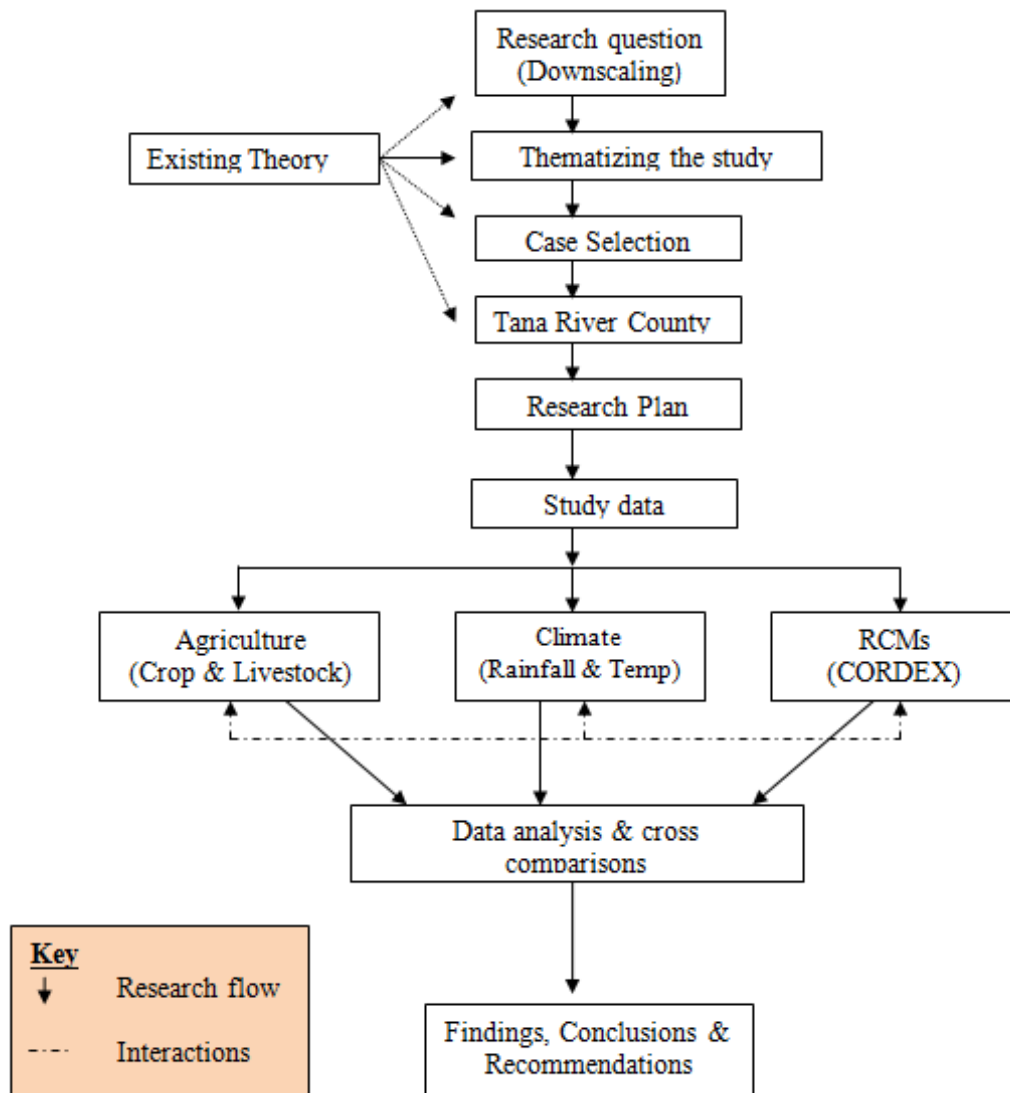


Figure 3: Schematic illustration of factors in the study case design (Source: Author, 2014)

3.4 Downscaling approaches

The two downscaling approaches employed in the study have specific set of assumptions, merits and limitations (see Appendix 1). The CORDEX RCMs used in the study were driven by the CMIP5 global climate models from the on-going CORDEX project. The models were integrated into the CORDEX-Africa domain (see Nikulin *et al.*, 2012; Endris *et al.*, 2013), with a horizontal grid spacing of 0.44 degrees. The simulations of the models for the period 1950 to 2005 were forced by natural and anthropogenic atmospheric gases under the IPCC's Representative Concentration Pathways (RCPs). The natural changes in atmospheric composition (GHGs) are associated with the ocean circulation changes and transitions between

glacial and interglacial episodes (EEA, 2012), while the anthropogenic causes relates the burning of fossil fuels, forest clearing and other industrial processes. The actual rainfall observations for 20 years (1989-2009) from six meteorological stations located in Tana River County were used to undertake model assessment and validation. Similarly, the relationship between agricultural production data and climatic characteristics (rainfall and temperature) used long-term available data in the region beyond the CORDEX RCMs data period.

3.4.1 Dynamical downscaling

This approach (also called nesting technique) was used to downscale GCMs using RCMs. The model projections were generated under the Representative Concentration Pathways (RCPs), which are based on radiative forcings (globally radiative energy imbalance) measured in $W\ m^{-2}$ by the year 2100 (Moss *et al.*, 2010). In this report, three RCPs are used namely RCP2.6, RCP4.5 and RCP8.5, which represent the low, mid and high-level emission and concentration scenarios respectively. The RCP2.6 emission and concentration pathway, also referred to as RCP3PD (Peak and Decline), represents a peak in radiative forcing at $\sim 3\ W/m^2$ ($\sim 490\ ppm\ CO_2$) by the mid-twenty-first century and then a decline to $2.6\ W/m^2$ by 2100. This scenario assumes optimistic mitigation measures and that the increase in the global average temperature will be limited below $2\ ^\circ C$. The RCP4.5 is a medium level concentration pathway that is assumed to stabilize radiative forcing at $4.5\ W/m^2$ ($\sim 650\ ppm\ CO_2$) and that this value will not be exceeded by the year 2100. The RCP8.5 pathway represents a high concentration pathway in which radiative forcing is assumed to reach $8.5\ W/m^2$ by the year 2100 ($\sim 1370\ ppm\ CO_2$) and then continues to rise thereafter. The RCP8.5 socio-economic pathway is characterized by rapidly rising population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long term, to high-energy demands and GHG emissions in the absence of climate change policies (Riahi *et al.*, 2011).

In this downscaling approach, the global climate change and variability is generated from CMIP5 GCMs used in the 5th IPCC report (IPCC, 2013). These GCMs have coarse resolutions (above $250\ km^2$) that undermine their accuracy in regional climate downscaling for impact assessment and thus future climate projections for the region (Katzfey *et al.*, 2009). CORDEX RCMs provides the opportunity to generate decision support climate information (Endris *et al.*, 2013) at regional or local scales that is useful for impact assessment and thus adaptation processes. The CORDEX RCMs were assessed against their simulation of the rainfall band due

to north-south movement of ITCZ, large scale climate forcing signals such as the ENSO and IOD together with their extreme impacts.

3.4.2 *Statistical downscaling*

The statistical technique relies on the fundamental concept that regional or local climate characteristics are largely a function of the large-scale atmospheric state. The statistical approach was applied to link agricultural production and climate data in correlation analysis. Further, the approach was applied in linking RCMs outputs to observed weather stations data. Simple linear correlations and statistical regression methods were applied. Multiple linear regressions was applied to cascade the climate information from coarse to fine resolution state through inference using deterministic function (f). The local climate and linear relationships can be expressed using the following equations 1, 2 and 3 respectively.

$$\text{Local climate variable} = f(\text{large scale variable}) \quad (1)$$

$$\begin{aligned} \text{Local climate} = f(\text{larger-scale forcing} + \text{fixed local forcing} + \text{variable local forcing} \\ + \text{random variable}) \end{aligned} \quad (2)$$

$$Y = f(X_1, X_2... X_p) + \varepsilon \quad (3)$$

Where $X_1, X_2... X_p$ are the independent variables (sea-level pressure, geo-potential heights and humidity) already inbuilt in the RCM, Y is the dependent variable (the required local climate information namely rainfall), ε is the random variable and f is the regression function.

In this study, the choice of statistical method which was also applied to relate crop production and climate characteristics in Tana River County are advantageous in terms of its efficiency, speed of simulation, relatively cheap and the less computational requirements as compared to the dynamical downscaling approach. The approach also uses average output of models, a technique often referred to as “ensemble”, rather than a single model and testing scenarios for many decades or even centuries. Wilby *et al.* (2002) indicated that the statistical approaches are used to gain better understanding of fine-scale variability, even down to point locations given the high-resolution data. However, the approaches have some inherent assumptions such as time invariance of the transfer function, relevance of predictors being

realistically modelled by the GCMs and the predictors being well represented in the GCMs information. The statistical technique also requires long and reliable observed historical data series for calibrations. Regarding the correlation and regression methods, the Pearson's correlation coefficient (r), which measures the strength and direction of association between the two measured variables, were determined with the significance level taken at 95% (null hypothesis was rejected if the p-value of correlation coefficient was < 0.05). In principal, the line of best fit through the data of two variables defines how well the data points fit the model. Statistical tables were used to confirm whether the correlation coefficient (r) is significant at $P \leq 0.05$. Thereafter, a regression analysis was performed when the p-value of the correlation coefficient was > 0.05 . The regression analysis was based on simple linear regression model $Y_i = \beta_0 + \beta_1 X_i + e_i$ [where, the expected value of a response variable (Y) is a linear function of the explanatory predictor (X), β_0 is the y intercept and β_1 is the estimate of the slope]. The model assumptions are that Y is normally distributed, X is fixed and random errors e_i are independent and identically distributed such that $E[e_i] = 0$, and $\text{var}[e_i] = \sigma^2$ [typically it is assumed $e_i \sim N(0, \sigma^2)$]. The model fit is estimated using multiple R-squared (R^2), residual analysis and F -statistic. Therefore, the estimation of model parameters was applied in hypothesis testing and determining the confidence intervals of CORDEX RCMs. This relationship formed the basis upon which downscaling climatic information for agricultural planning and impacts studies were developed for recommending implications to decision makers.

3.5 Future projections

Future projections of rainfall and temperature characteristics in Tana River County and eastern African region were done using ensemble of CORDEX RCMs. The study evaluated the performance of CORDEX RCMs compared to the semi-observed European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) and rainfall records obtained from six weather stations located in Tana River County. The simulation of rainfall characteristics of the study area provides higher degree of confidence in the individual models and subsequently the ensemble model for future climate studies. The validation of ensemble model was done using observed rainfall records from six weather stations to enhance confidence level in projecting future rainfall and temperature scenarios in the study area. The projection of plausible future rainfall and temperature scenarios on seasonal timescale up to 2100 were done using IPCC RCP 2.6, 4.5 and 8.5 emission scenarios. The RCP 4.5 is an intermediate emissions

where the radiative forcing is stabilized shortly after year 2100, consistent with a future with relatively ambitious emissions reductions (compared to B1) while RCP 8.5 is consistent with a future with no policy changes to reduce emissions as in A1B1 used in the Fifth Assessment Report (AR5).

The projection findings from the study area were used in recommending the implications on crop and livestock production systems so as to mainstream appropriate adaptation solutions into various agricultural planning and decision making activities in Tana River County. Future projections were considered both at short and long term time scales. The short term projected information (2030 timeframe) were considered significant and relevant for agricultural planning, decision making and implementation of targeted climate change adaptation initiatives and this is also in line with Kenya's vision 2030 development plan. The considered projection time scale is particularly critical in informing the present and future adaptation pathways planned by decision makers in various economic sectors. The projected future rainfall and temperature change information was envisaged to provide better understanding on the plausible climatic scenarios and their impacts on the sensitive agricultural production systems. Based on this projected climatic changes and impacts, various specific recommendations on appropriate coping and adaptation measures were formulated for consideration by the agricultural managers, natural resource managers, pastoralists and individual farmers in the region.

3.6 Data collection

Generally, the study data collection activity comprised the field work at Tana River County and laboratory model simulations at Inter-Governmental Authority on Development (IGAD) Climate Prediction and Applications Centre (ICPAC) regional office in Nairobi. Field data collection in Tana River County included the climate and agricultural production data. Several levels of consultations were held in the region with key stakeholders (see Plate 2) to introduce the study research project, establish contact persons for engagements during the study period, document key baseline information and plan research activity timeframes.



Plate 2: Research consultative meetings held in Tana Delta Sub-county, February- March, 2012

Focused Group Discussions (FGDs) and personal interviews were employed using structured questionnaire (Appendix 2) to generate insightful qualitative data. The key informants were carefully selected based on purposive randomized sampling approach taking into consideration informants occupation in society, geographical location, knowledge on climate related events and age which is linked to long-term experience and observations on extreme climatic events such as drought and floods in the region. Members of FGDs comprised representatives of village elders/headmen, chiefs, opinion leaders, clergymen, professionals and lead farmers. At least two focused group discussions (FGDs) in every sub-county namely Tana Delta, Tana River and Tana North were used. Further, data and information were obtained from a cross-section of farmers in the County regarding their perceptions on the changing climate and impacts with specific focus on coping mechanisms, implemented adaptation measures and existing government supported programmes in the region.

Study data collected in Tana River County comprised of climate, agricultural productions (crops and livestock) and CORDEX RCMs as discussed below. Other secondary data collected to complement field data included past research reports focusing on Tana River County discussing the impacts of changes in rainfall, temperature and extreme events (floods and droughts) in the region.

3.6.1 Climate data

The study climate data was limited to two variables namely rainfall and temperature due to their direct and significant contribution to agricultural yields, productivity and other livelihood

sources in the region. The two selected parameters are key determinants of agricultural production and largely determine the distribution of crops and livestock as well as their productivity, choice of what plant to cultivate, how to cultivate it, yields of crops and nature of livestock to keep. Changes in rainfall and temperature directly affect crop production and alter the distribution of agro-ecological zones. Rainfall is the dominant controlling variable in tropical agriculture since it supplies soil moisture for crops and grasses for livestock. The long-term observed climate data were obtained from KMS weather stations located in Tana River County namely Tana, Garsen, Garissa, Kipini, Witu and Bura (see Figure 4). The climate data comprised of weather stations and their distribution, monthly rainfall and monthly temperature. The data period from the stations varied but ranged from 1951 to 2011.

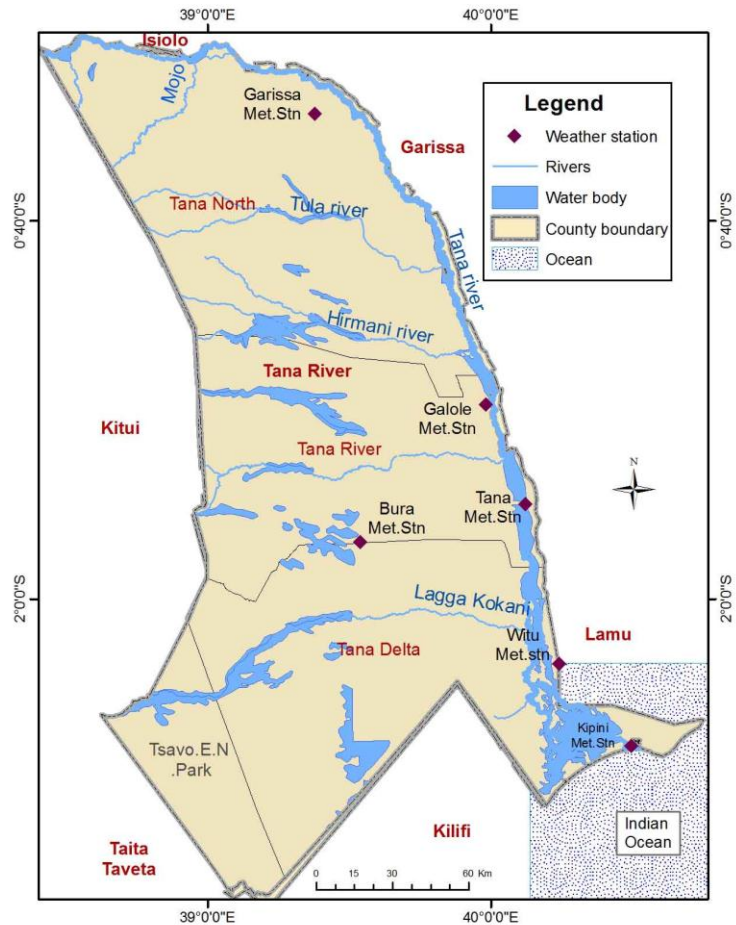


Figure 4: Weather stations in Tana River County used in the study (Source: Author, 2015)

Since climate information extends beyond the administrative boundaries, data from other neighbouring weather stations were considered such as Masalani and Lamu, which were used to

support regional understanding of the climatic changes. Weather stations in the region were further classified according to KMS grading system that classifies a weather station as either grade A or B based on the level (types) of data recorded. Five weather stations in Tana River County were classified as B and 1 grade A defined as synoptic station. Grade B stations in the region were operated by KMS in conjunction with other organizations such as the Ministry of Agriculture, Universities, Agricultural Research Institutions or large scale private farms.

The Global Precipitation Climatology Centre (GPCC) data, the largest compilation of global monthly in situ observed precipitation dataset (1901- 2011), were used in validating CORDEX models regional rainfall estimation. GPCC data are time series data sets of above 10 years duration from more than 67000 different stations and are recommended for global and regional studies. These geo-temporal data coverage allows for the issuance of re-analysis products covering the 111 years.

3.6.2 Crop and livestock data

Long-term agricultural data comprised of commonly grown crops and yields, livestock types and population. This data were collected from Ministry of Agriculture, Livestock and Fisheries (MALF) departments at sub-counties agricultural extension offices (Tana Delta, Tana North and Tana River), Kenya Agricultural and Livestock Research Organization (KALRO) centres (Mpeketoni and Garissa) and Department of Resource Surveys and Remote Sensing (DRSRS). Crop yields (tons/acre) comprised of the commonly grown crops in the area under rain-fed farming system namely maize, green grams, rice, cassava and mangoes. Similarly, livestock data comprised of livestock types and their annual population. Agricultural data for correlation with CORDEX data was limited to 1989-2008 to coincide with CORDEX data available from 1989 to 2008.

3.6.3 CORDEX RCMs data

This data was sourced and analyzed at ICPAC regional office in Nairobi. The data consisted of downscaled monthly rainfall and temperature available from 1989 to 2008 for evaluations and 2006 to 2100 for future projections. Appendix 8 illustrates a full list of the CORDEX RCMs used, institute responsible and country, their short names, details of their dynamics and their physical parameterizations. Detailed information on each model outputs can be obtained from Nikulin *et al.* (2012). The RCMs were forced by lateral and surface boundary

conditions from the ERA-Interim. A baseline model run was undertaken for a period of 20 years (1989 to 2009) forced by analyses of observations (ERA-Interim reanalysis data) to provide a benchmark framework for individual model evaluation and assessment. CORDEX models were then evaluated for seasonal (MAM & OND) and annual rainfall climatology at regional (eastern Africa) and local scales using GPCP and Tana River County weather stations observed data respectively. The projected future rainfall and temperature scenarios for Tana River County were limited to 2030, 2050 and 2070 timeframes to coincide with Kenya's development plans. These plausible future outcome scenarios were used in recommending climatic implications on future agricultural production activities for informed planning decisions that synchronises the activities with the projected climatic events and their uncertainties.

3.7 Data sampling

Data sampling procedures for various data sets collected in Tana River County were considered so as to obtain generalisable information about climate change and variability being studied. A non-probability purposive random sampling technique (also known as judgmental, selective or subjective sampling) was adopted in selecting participants for the Focused Group Discussions (FDGs) and personal interviews conducted in Tana River County. In this technique, the samples being studied is not representative of the population and the choice was because the study was pursuing participants with definitive occupation in society, geographical location, skills on climate related events and age which is linked to long-term experience and observations on extreme climatic events such as drought and floods in the region. The sampling frame was carefully selected with the assistance of County agricultural extension staff. The representative sample for the FDGs comprised of representatives of village elders/headmen, chiefs, opinion leaders, clergymen, professionals and lead farmers. Structured set of questions (Appendix 2) was used during the discussions in the FDGs and interviews.

3.8 Data reliability and validity

The reliability and validity of various study data were carefully considered as it affected study conclusion and recommendations. Quality control tests for climate data (rainfall and temperature) were done using single mass curves to verify their consistency and continuity (homogeneity tests). The missing rainfall records in the study weather stations were estimated using cross correlation approach using nearby stations (Masalani, Lamu and Malindi) with

highest correlation coefficient to the station with the missing data in the same period. Similarly, stochastic weather generator MARKSIM was used to generate synthetic rainfall and temperature data where necessary. Box plots were used to check the normality assumption (data outliers) present in rainfall and crop data sets. Detected data outliers (values) were carefully expunged from analysis due to its sensitivity in parametric statistics. However, they were considered for further investigation. All field data (rainfall, temperature, crop yields, livestock types and numbers) were cross-checked for typographical and computer entry errors before running data analyses. For crop data, conversions of yields from bags per acre to tons per acre were carried out before data analysis and to ease interpretation. Other general data quality compliances done during the study include maintaining data records, accurate data entry into computer and organizations and checking data accuracies at all stages.

3.9 Data management

Research data is a critical resource in making research conclusion and recommendations regarding the study objectives (Beagrie, 2010). In summary, study data consisted of CORDEX RCMs data; climate data; rainfall (monthly, seasonal and annual), temperature (monthly and annual), crop yields for five selected crops, livestock types and numbers. The study data management process adopted comprised of designing data collection instruments, management of field data sheets, accurate data computer entry and its organization in computer files, checking for data accuracy, maintaining records of the processing steps and archiving data for future reference and access. Field data collected were properly organized through excel spread sheets, word documents and stored in computer files for easy retrievals, editing and analyses.

3.10 Data analyses

Exploratory tools were utilized in the initial stages of field data analyses which include tables, charts and summary of statistics graphs (box plots, and time series) to illustrate the main data patterns or the underlying structure in data relative to study objectives. Box plots were used to identify data outliers present in crop and rainfall data, which have a large effect on the reliability of linear functions, correlation coefficient and key statistical tools used in this study. Further, outliers have a strong influence over the fitted slope and intercept giving a poor fit to the bulk of the data points, and often have a tendency to mislead study conclusions. Outliers usually tend to increase the estimate of residual variance and lowering the chance of rejecting the null

hypothesis. Use of box plots provided critical information on the normality of data distribution (the symmetric nature of box plots where median and mean, which are together in the middle of the box). However, the existence of few climate data points in ASALs made it hard to detect non-normality.

Data exploration was carried out for both climate and agricultural production data to generate preliminary findings addressing their characteristics in the region. Descriptive statistics such as the minimum and maximum values, running averages, range, standardized anomalies and coefficient of variation were further used to explore crop yields and climate data. Single-mass curves were used to analyze the consistency and homogeneity of rainfall and temperature data collected from the six weather stations in Tana River County. Time series graphs were used to reveal data variability and trends of historical rainfall, temperature and agricultural yields. Rainfall anomalies graphs were plotted to describe trends of enhanced/depressed rainfall in the region associated with rainfall in relation to floods and droughts. The thresholds for extreme climatic events (drought and floods) were expressed in terms of rainfall departure from normal over some period of time (meteorological drought and flood). Bi-variate correlations and simple linear regression analyses were done between crop yields/livestock numbers and seasonal/annual rainfall to measure their relationships which informed projection of future scenarios. The correlation coefficient was calculated with the significance level taken at 95% (null hypothesis was rejected if the p-value of correlation coefficient was < 0.05). The Pearson's correlation was used to measure the strength and direction of association between the two focused variables. In regression, the Multiple R-Squared (R^2) was used to quantify model performance (Winkler *et al.*, 1997) and P-Values used to test the significance of the coefficient associated with the independent variable in the equation. A summary of data analyses tools used in the study analyses and the applied statistical tests are illustrated in Table 3.

Analyses of CORDEX RCMs simulations were done in relation to how models depicted or reproduced rainfall characteristics of the study region (including for the eastern Africa). Model verifications (accuracy) revolved around their performance in reproducing the annual and seasonal rainfall characteristics for Tana River County in comparison with the observed spatial plots from weather stations. The CORDEX models simulation biasness with the observed characteristics were evaluated using the GPCC datasets. The performance of the RCMs in reproducing the observed or reanalysis statistics were measured using correlation coefficients

and distance measures (R), root mean squared error (RMSE), mean absolute error (MAE), relative absolute error (RAE), and root relative squared error (RRSE). To assess the consistency of the models in representing the spatial distribution of rainfall with time, spatial and temporal correlations between observed or simulated rainfall were performed for each year. The assessments of the capacity of CORDEX RCMs to capture the inter-annual variability of rainfall in Tana River County involved temporal analysis of the averaged observed or simulated climate data. The coefficient of determination (R^2) was used to determine the significant correlations. Composite analysis approach was also used to assess the performance of CORDEX RCMs to reproduce rainfall anomalies that are associated with large scale circulations factors influencing the eastern Africa rainfall variability (ENSO and IOD).

Table 3: Summary of statistical data analyses

Specific objective	Null hypothesis (H_0)	Variable		Statistical data analyses tools
		Dependent	Independent	
To evaluate the performance of CODEX RCMs in simulating rainfall and temperature characteristics in Tana River County	CORDEX RCMs do not accurately simulate the observed rainfall and temperature characteristics in Tana River County	Observed rainfall & temperature	Simulated rainfall & temperature	<ul style="list-style-type: none"> • Correlation coefficients (R) • Root mean squared error (RMSE) • Multiple R-Squared (R^2) regression

Specific objective	Null hypothesis (H ₀)	Variable		Statistical data analyses tools
		Dependent	Independent	
To evaluate the impact of rainfall and temperature on the agricultural production of Tana River County	There is no statistically significant relationship between rainfall and temperature characteristics and agricultural production in Tana River County	Crop yields (maize, cassava, rice, mangoes & green grams); Livestock population (numbers)- goats, sheep, cattle, camels,)	Rainfall Temperature	<ul style="list-style-type: none"> • Instat+, GenStat • P-Values • Pearson's R • Time series analysis • Bi-variate correlation • Simple linear regressions
To project future rainfall and temperature changes in Tana River County and their implications on agricultural production and related land resources	Future rainfall and temperature in Tana River County would not adequately support agricultural production and related land resources	Observed rainfall & temperature	Simulated rainfall & temperature	<ul style="list-style-type: none"> • Temporal & spatial correlations • RMSE

(Source: Author, 2013)

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents and discusses the results obtained from the various methodologies adopted to address the study overall and specific objectives. The chapter consists of four broad sub-sections; the first section discusses the results from quality control on in-situ stations observed data used in the study; the second section examines the performance of CORDEX RCMs in simulating rainfall and temperature characteristics in Tana River County and eastern Africa region; the third section discusses the characteristics of observed rainfall and mean surface temperature together with their relationships with crop and livestock productions; and finally the fourth section discusses the implications of the projected warming and rainfall variability on agricultural production and related land based resources in Tana River County and proposed recommendations to combat the effects. Although the study focused on Tana River County, the results and discussions in this chapter recognize that climate change and variability together with its drivers are global and regional in nature. Thus, it incorporates results of model assessment (downscaled climate information) for eastern Africa and Kenya as a benchmark for model verification as well as putting clarity on the study findings regarding the local scale climate change information.

4.2 The performance of CORDEX RCMs in simulating rainfall and temperature characteristics in Tana River County

4.2.1 Introduction

This section examines the performance of CORDEX RCMs in simulating rainfall and temperature characteristics of Tana River County. The simulated model results are compared with the observed weather stations characteristics on seasonal, annual or decadal basis. Good models are statistically measured on the basis of reproducing the observed climatology of a region. Although this study focused on Tana River County, the section recognizes that climate change and variability together with its drivers are global and regional in nature. Thus, it begins the analyses by assessing models performance in capturing the regional large scale systems that influences Tana River climatology such as the ENSO and ITCZ movements. Models assessment

in the eastern Africa region provided a baseline for model verification with the results increasing the confidence in CORDEX RCMs to assess Tana Rover County characteristics.

4.2.2 Performance of CORDEX RCMs in simulating eastern Africa rainfall

Figures 5 and 6 illustrate the simulated mean rainfall characteristics of CORDEX RCMs for MAM and OND seasons respectively over the eastern Africa region. All the models were found to realistically simulate the rainfall climatology over the region associated with the Inter-tropical Convergence Zone (ITCZ) movements during the two seasons with over 84% coefficients of correlation. The capturing well the ITCZ belt movement in the tropics ($r > 0.84$) is an indicator of good model performance in the region. The RCMs reproduced fairly well the low precipitation thresholds over the arid and semi-arid areas of the region and specifically the Tana River County represented by the rectangular grid box.

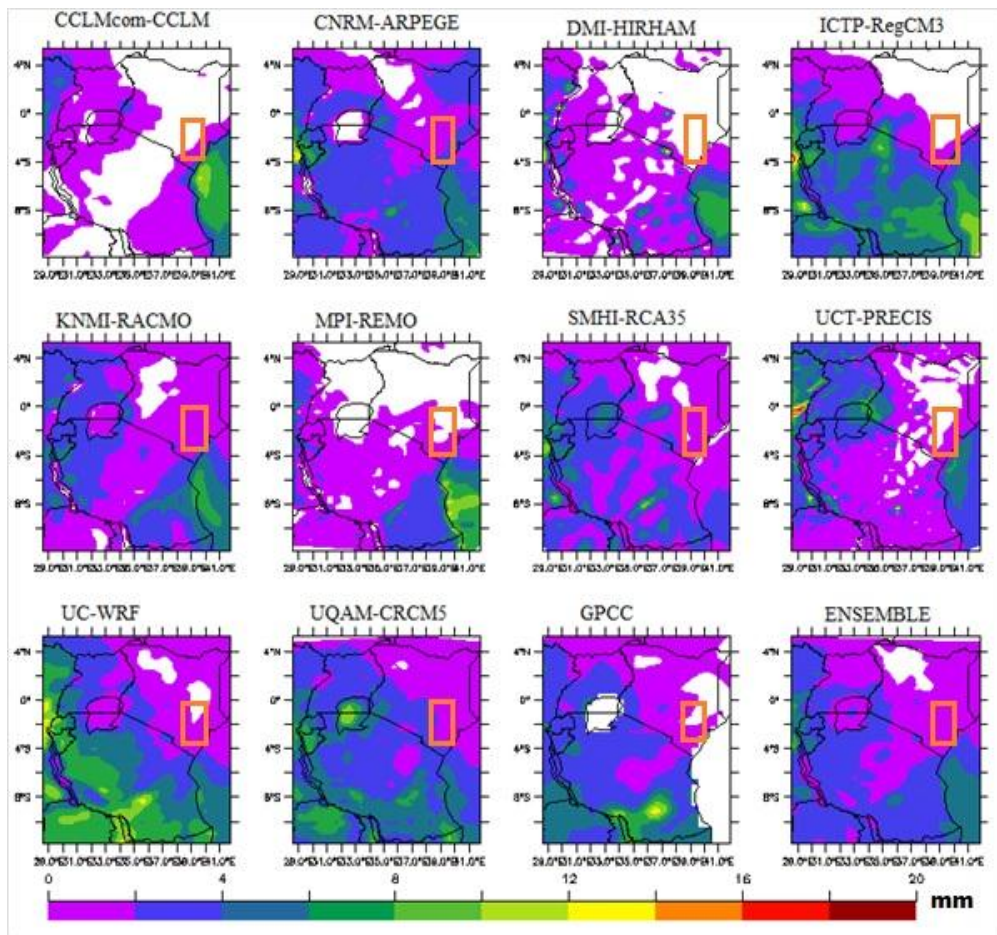


Figure 5: Rainfall characteristics of eastern Africa during MAM rainfall season as simulated by CORDEX RCMs, GPCC and ensemble RCM

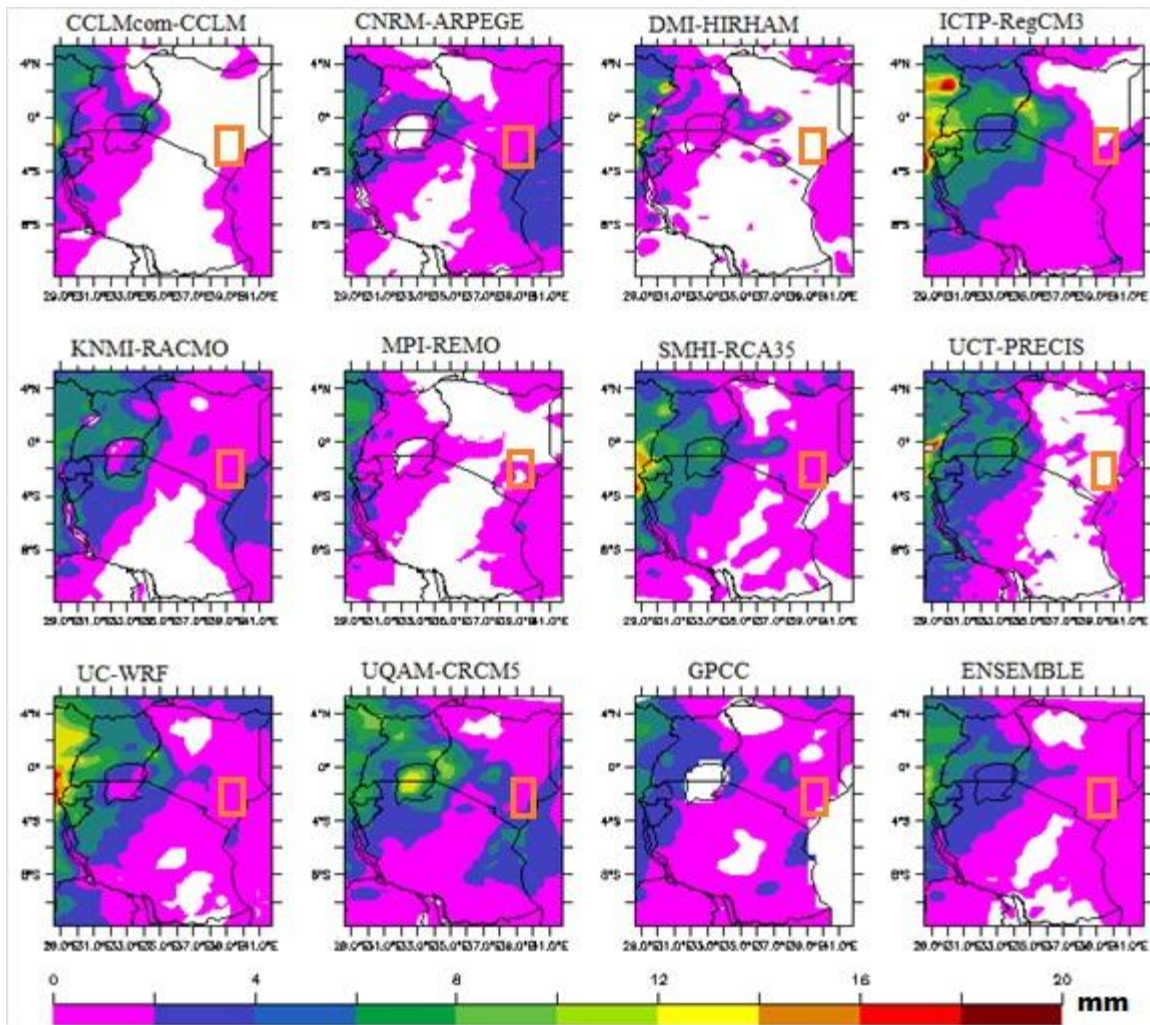


Figure 6: Rainfall characteristics of eastern Africa during OND rainfall season as simulated by CORDEX RCMs, GPCC and ensemble RCM

Figure 7 below illustrates CORDEX RCMs validation results in Tana River County during the MAM rainfall season.

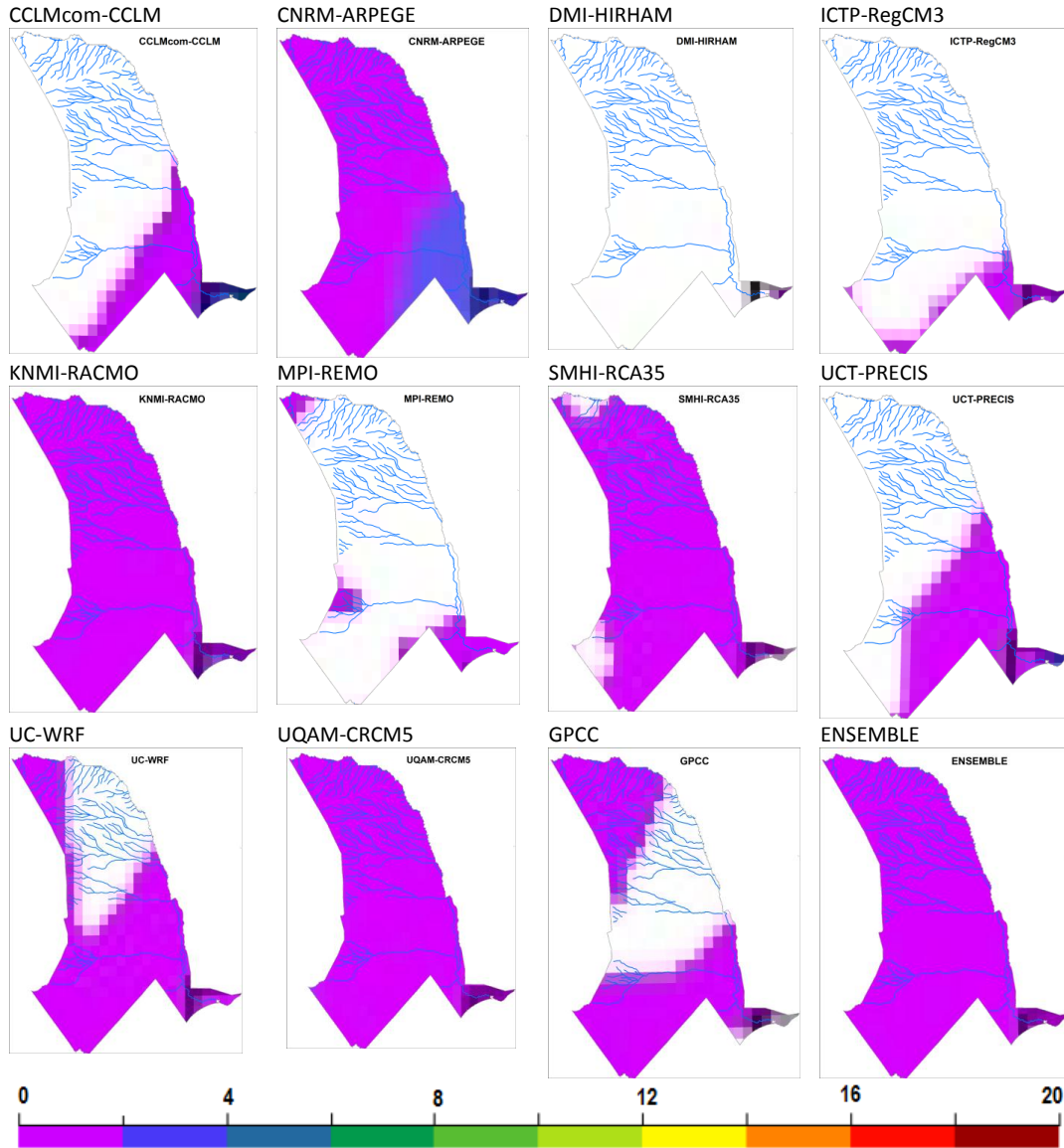


Figure 7: Tana River County MAM rainfall characteristics as simulated by CORDEX RCMs, GPCC and ensemble RCM

Accuracy of models in simulating the regional rainfall characteristics (biasness of models) is demonstrated in Figures 8 and 9. The results illustrate the differences between CORDEX RCM values and that of the GPCC for MAM and OND seasons respectively. Most of the RCMs simulate dry biases over the arid and semi-arid areas (including Tana River County) which suggest that the error is due to an error simulated by ERA-Interim (ERAINT). In most of the RCMs a dry bias was observed over north and eastern Kenya together with central Tanzania. It was however noted that the 10 RCMs generally indicated wet bias over western Uganda and the Lake Victoria basin.

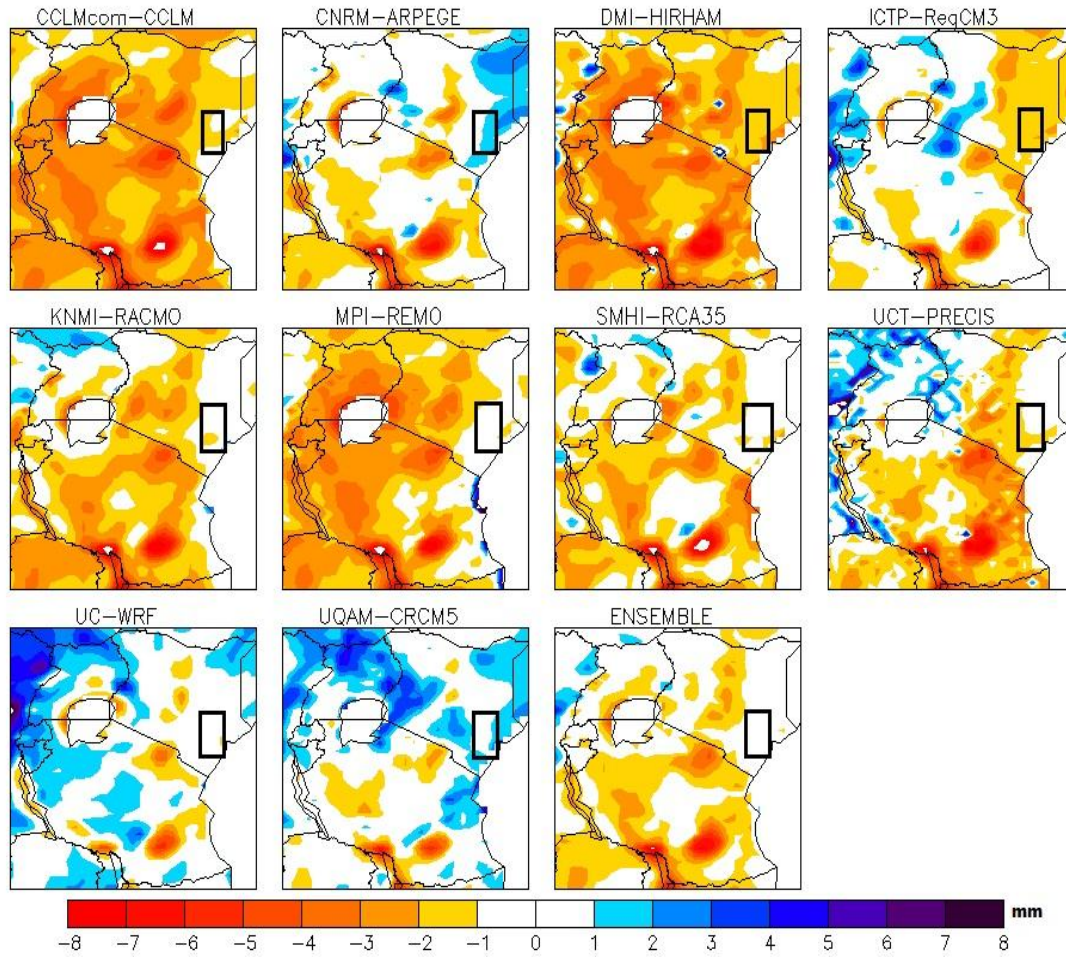


Figure 8: CORDEX models biasness over the eastern Africa and Tana River County during MAM season (1989-2009)

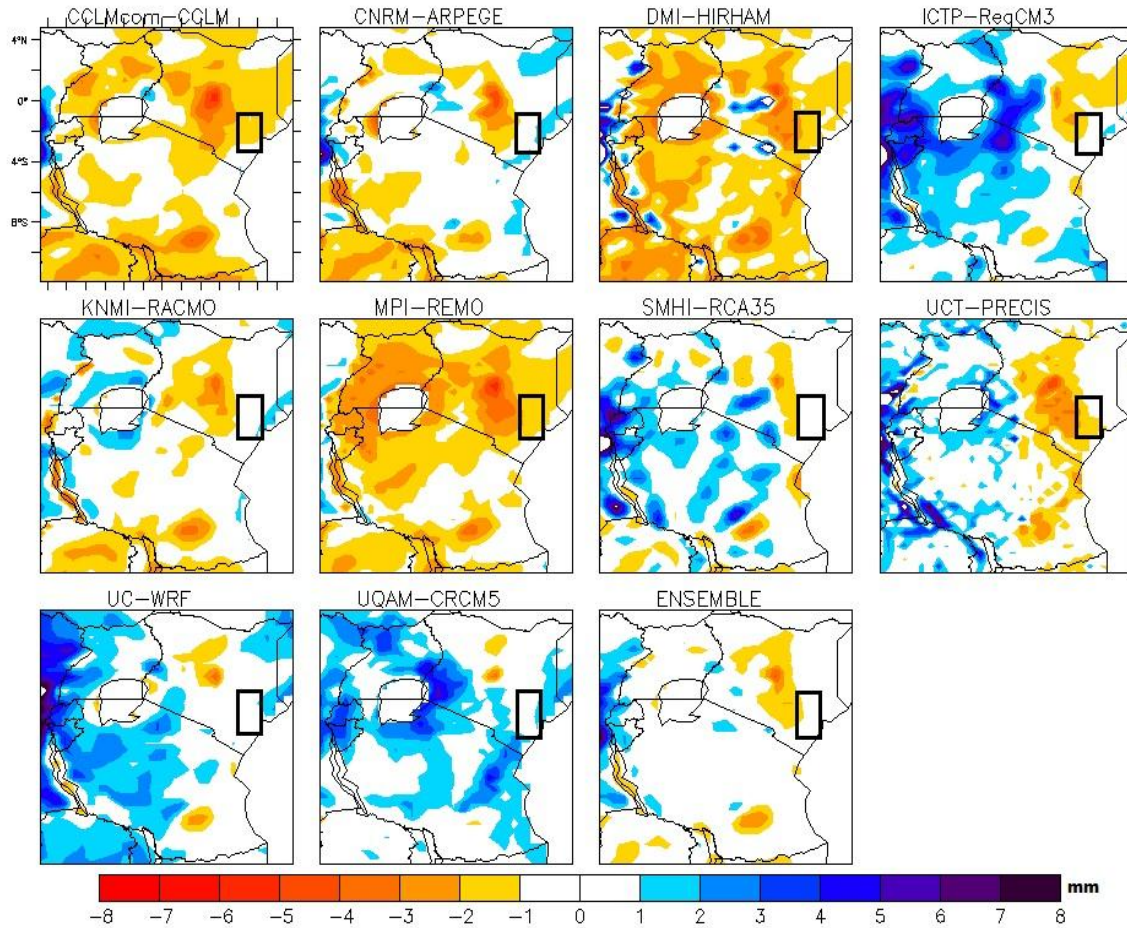


Figure 9: CORDEX models biasness over the eastern Africa and Tana River County during OND season (1989-2009)

It is however worth noting that models CCLM, ARPEGE, HIRHAM, and REMO show dry bias in reproducing OND rainfall nearly in all parts of the region. However, ERAINT simulates lower threshold values than GPCC. The ERAINT biases may be attributed to the low resolution and shortcomings in convective parameterization of the GCM used for ERAINT.

4.2.3 Performance of CORDEX RCMs in simulating mean annual rainfall cycle over eastern Africa

Figure 10 illustrates the results of CORDEX RCMs, GPCC and ensemble RCM in simulating the mean annual rainfall cycle over the equatorial region of eastern Africa. The results demonstrate that most CORDEX RCMs capture the shape of annual rainfall seasonality of the region (eastern Africa) which comprises of long (MAM) and short (OND) rain seasons in a year with observed peaks in April and November respectively (see Figure 12). However, some models such as UC-WRF and CNRM-ARPEGE overestimate the magnitude of the rainfall seasons especially during MAM and OND. The ensemble RCM was found to have relatively good performance as compared to the individual models. In general, there was fairly good agreement between the annual rainfall cycle simulated by CORDEX RCMs and the actual observation by GPCC over the equatorial of eastern Africa.

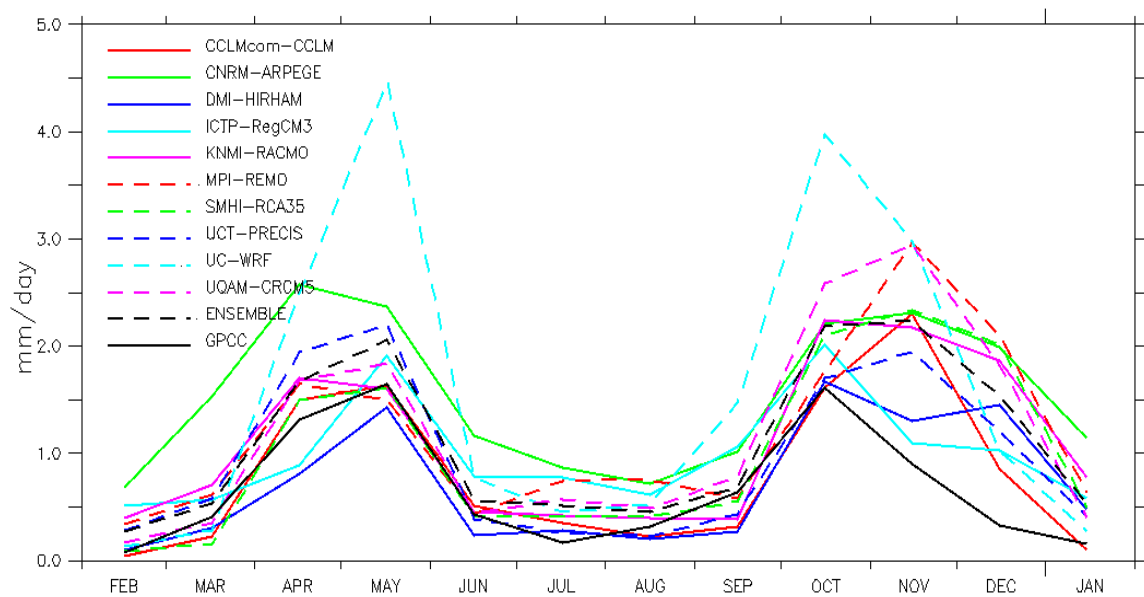


Figure 10: Mean annual rainfall cycle over the equatorial region of eastern Africa as reproduced by CORDEX RCMs, GPCC and ensemble RCM

4.2.4 Performance of CORDEX RCMs in simulating large-scale global climate forcing signals

The performance of CORDEX RCMs to simulate large-scale global climate forcing signals such as El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) for inter-annual variability over the equatorial sector is illustrated in Figure 11.

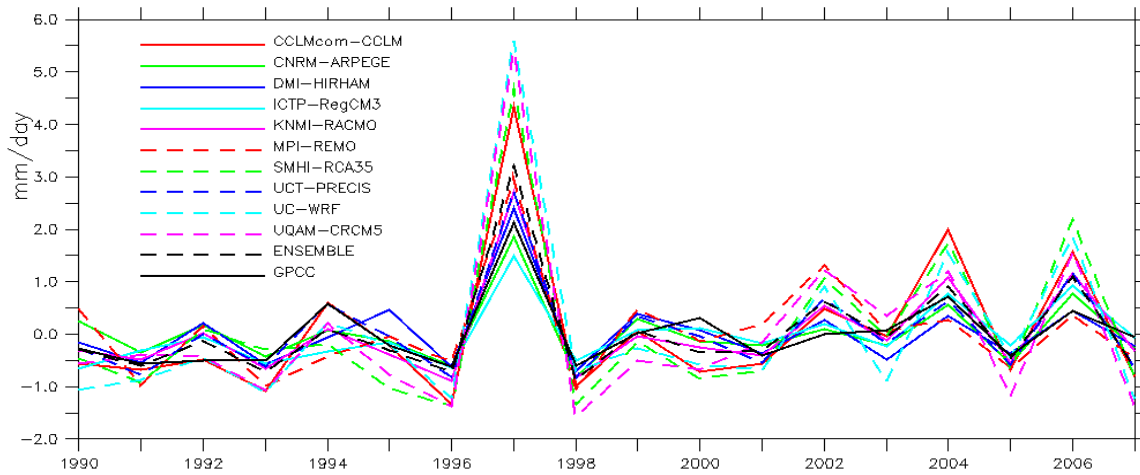


Figure 11: CORDEX RCMs performance in simulating inter-annual precipitation variability over equatorial sector

The above results show that almost all the RCMs realistically simulate the inter-annual rainfall variability, conspicuously is the 1997 high rainfall event that was associated with strong El Niño in phase with positive IOD. On the other hand, RegCM3 and UC-WRF do not capture well the inter-annual rainfall variability as compared to the observed.

4.2.5 Performance of CORDEX RCMs in simulating Tana River County rainfall characteristics

After analysing the accuracy of the model on the regional scale (model accuracy tests), the performance of the CORDEX RCMs was then assessed over the study area (as hypothesized) by simulating the rainfall characteristics and comparing to observed rainfall records from weather stations located in the region. Generally, the observed annual rainfall sequence from all the stations in the lower Tana basin revealed the bimodal nature of seasons; March-May (MAM) and October-December (OND) with peaks in April and November respectively as illustrated in Figure 12.

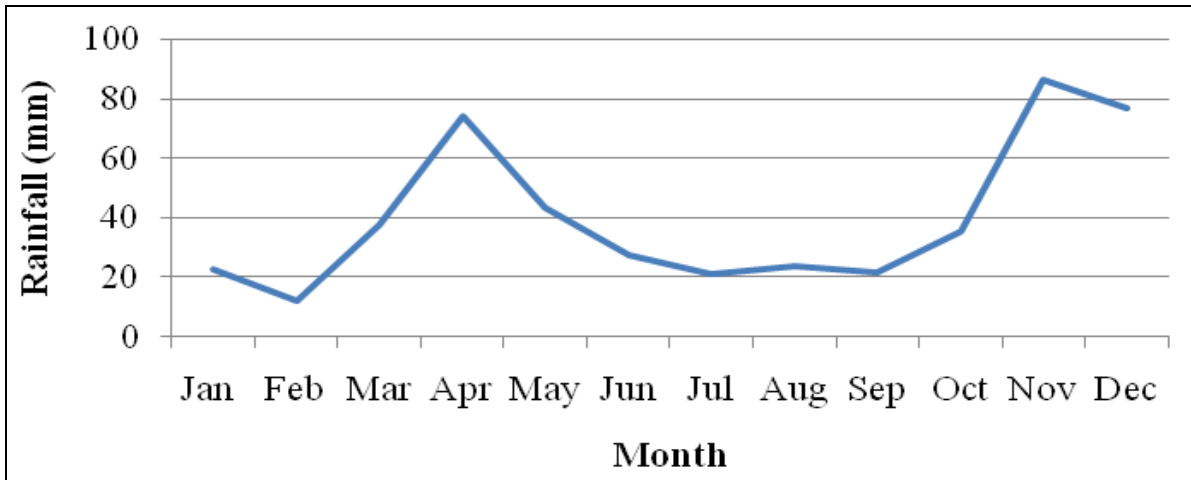


Figure 12: Observed annual rainfall sequence from the Garissa weather station records

Figure 10 illustrated simulated CORDEX RCMs results over the eastern Africa region (Tana River included). Comparisons of the simulated (Figure 10) and observed mean annual rainfall trends (Figure 12) all reveal the bimodal trend of the rainfall seasons with over 90% agreements. Further, the temporal rainfall trend over Tana River County (Figure 11) clearly reaffirms the ITCZ as the large scale climate driver associated with rainfall seasonality in the region. The findings demonstrate that CORDEX RCMs exhibit only a slight or negligible dispersion from observed rainfall climatology in Tana River County. The result therefore affirms the adequacy (good performance) of CORDEX models in simulating the rainfall characteristics of Tana River County.

In summary, CORDEX RCMs simulated fairly well Tana River County and eastern Africa rainfall climatology and therefore appropriate for application in projecting future rainfall scenarios for Tana River County and the region at large. The ensemble models generally displayed good performance as compared to any individual RCM. The UC-WRF model was found in all the analyses to significantly overestimate rainfall. Although CORDEX models simulated the observed climatology of Tana River County and eastern Africa, models overestimate rainfall and further studies need to be carried out in other regions. These further evaluations are critical in characterizing the strengths and weaknesses of these models for their use in producing future regional climate change projections when the lateral boundary forcing is provided by multiple GCMs and emissions scenarios from the CMIP5 archive.

4.2.6 Performance of CORDEX RCMs in simulating temperature characteristics

Figure 13 illustrates the results of CORDEX RCMs simulation for Tana River County and eastern Africa region during the MAM season. The models reveal relatively homogeneous temperature conditions across Tana River County and concur well with the observed temperature characteristic from weather stations. Models simulated between 20 to 30°C temperature values in the entire County as illustrated in Figure 13.

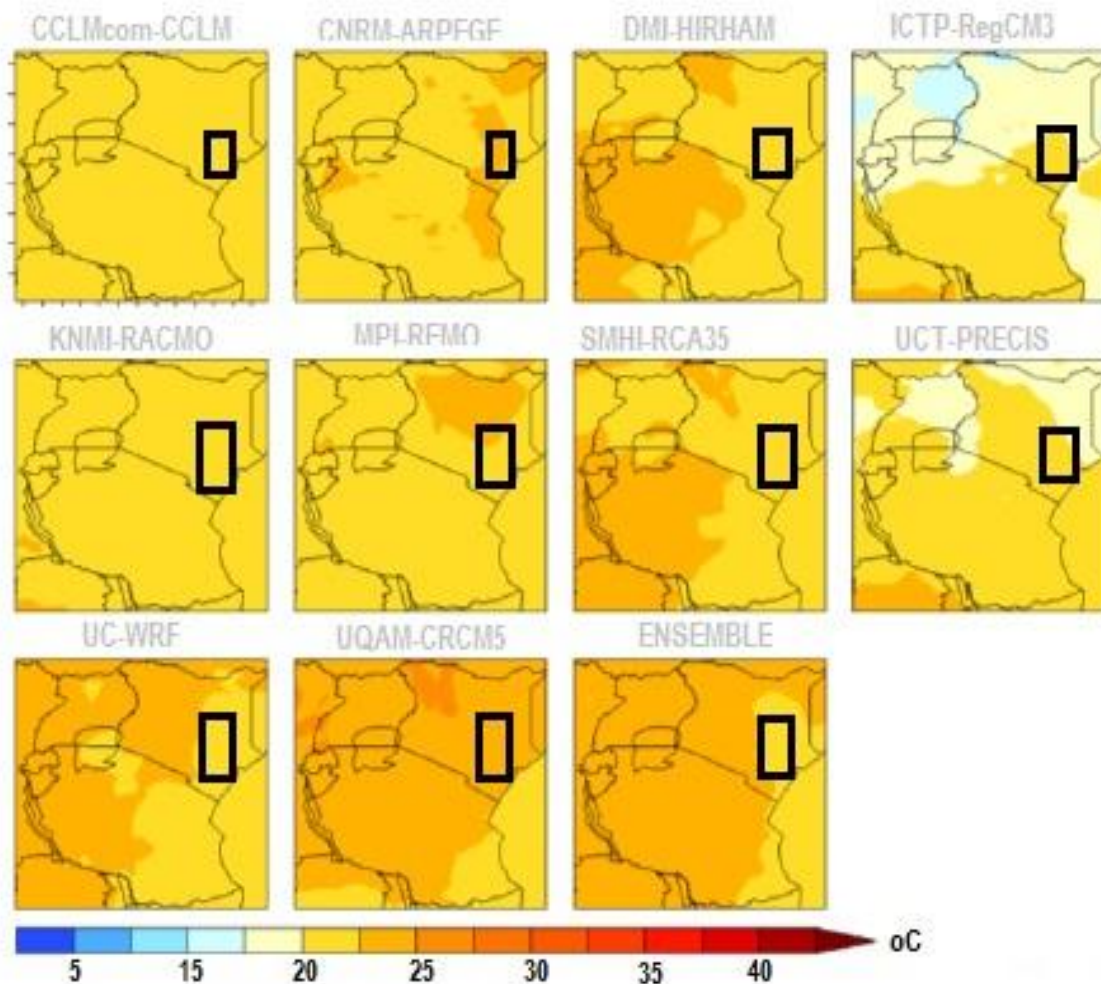


Figure 13: Mean surface temperature characteristics of Tana River County and eastern Africa during MAM season as simulated by CORDEX RCMs, GPCP and ensemble RCM

Similarly, models simulated higher temperatures during the OND season implying more warming conditions in the region with temperature rising up to 35°C with UCT-PRECIS model as illustrated in Figure 14.

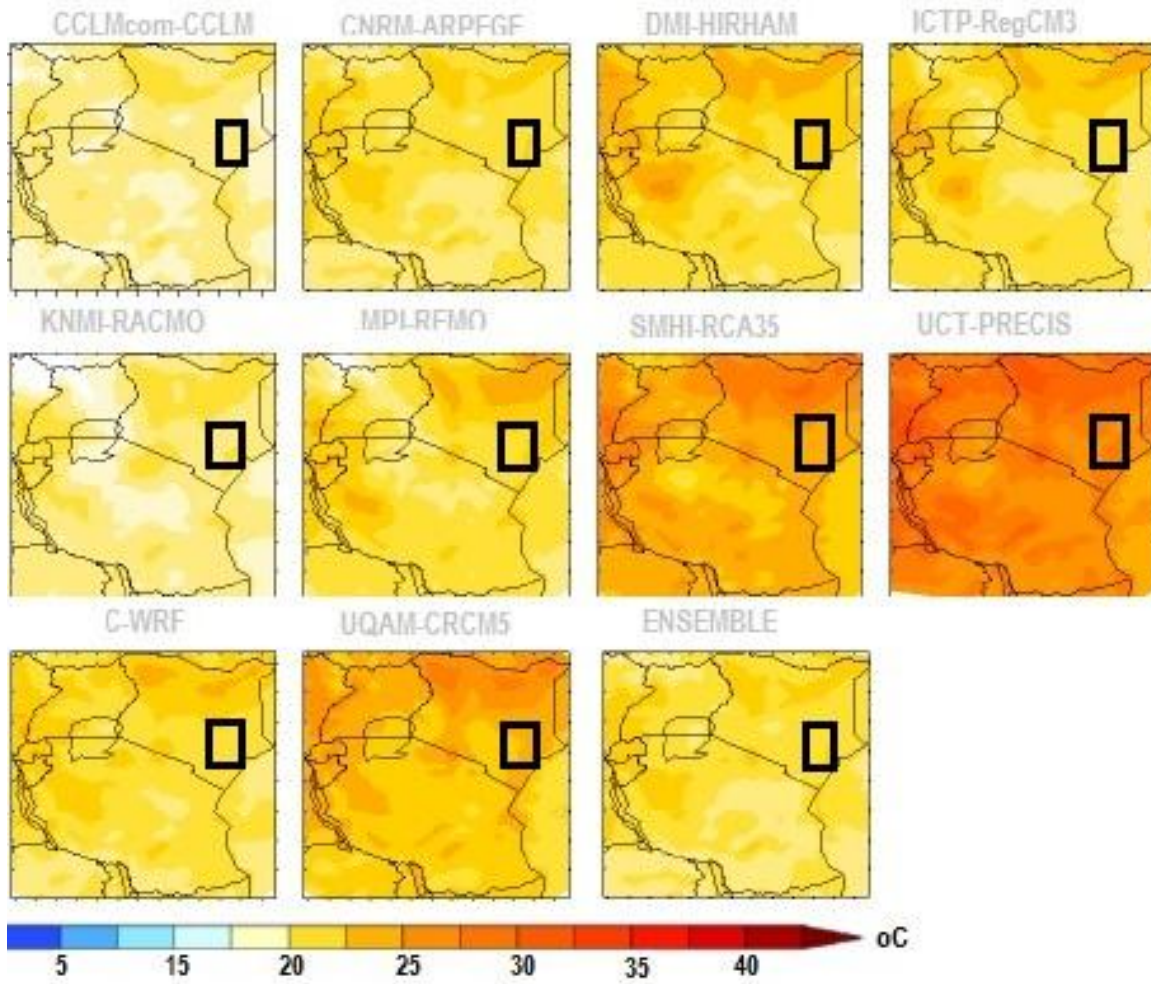


Figure 14: Mean surface temperature characteristics of Tana River County and eastern Africa during OND season as simulated by CORDEX RCMs, GPCC and ensemble RCM

Further, Figure 15 illustrates the 50km resolution temperature characteristics for Tana River County as simulated by the ten CORDEX RCMs. The results clearly illustrate the spatial homogeneity of temperature characteristics in the region and concur well with the observed.

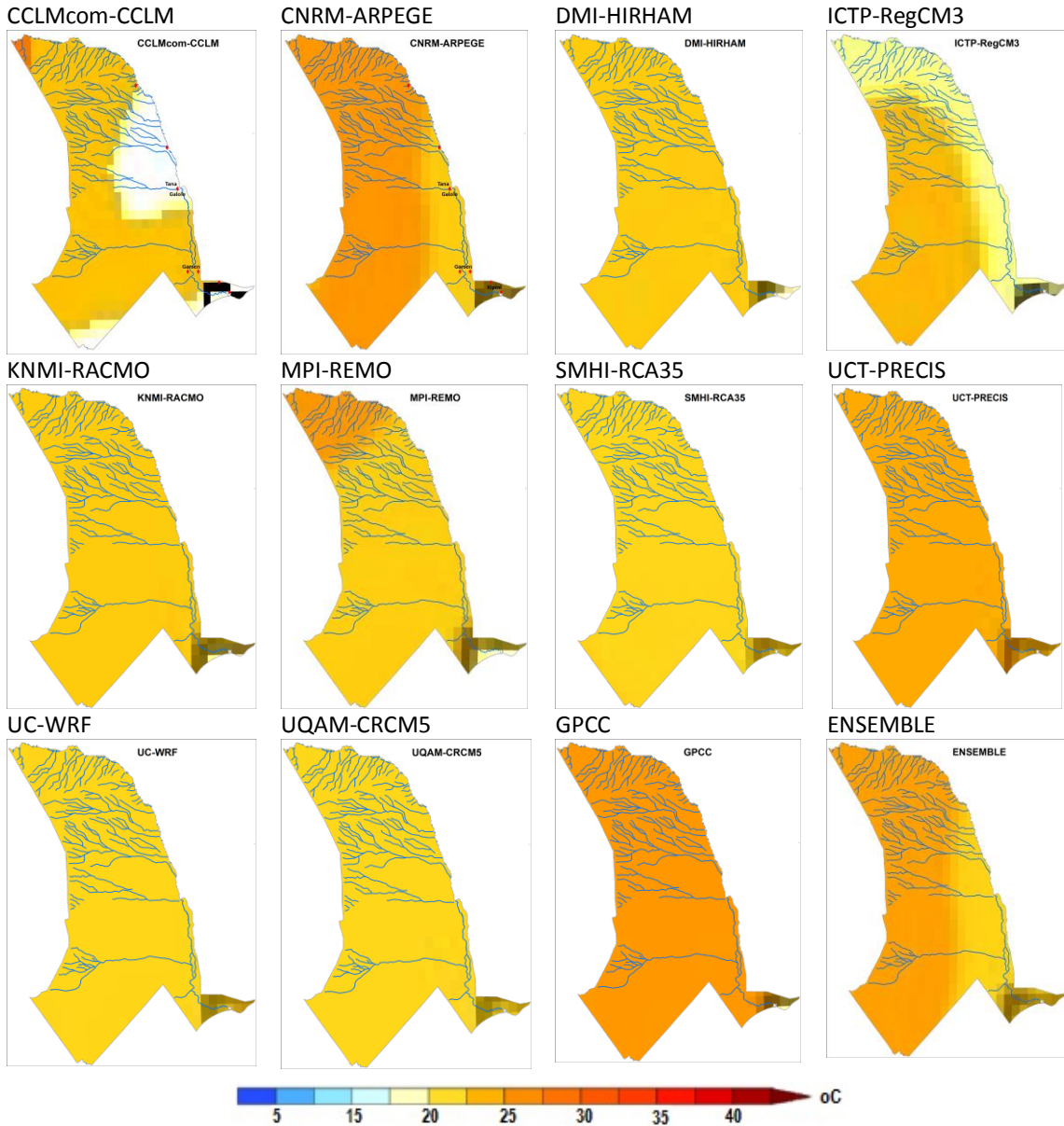


Figure 15: Mean surface temperature characteristics of Tana River County during MAM season as simulated by CORDEX RCMs, GPCC and ensemble RCM

4.3 Agricultural production and climate in Tana River County

4.3.1 Rainfall and temperature homogeneity tests

Rainfall data homogeneity tests (MAM and OND seasons) for six weather stations located in Tana River County (Garissa, Tana, Galole, Bura, Witu and Kipini) are illustrated in Figure 16 below. The results exhibit straight lines, an evidence of data continuity and consistent. The straight single line fitted to the cumulative rainfall records, an indication of homogeneity and quality records for the study.

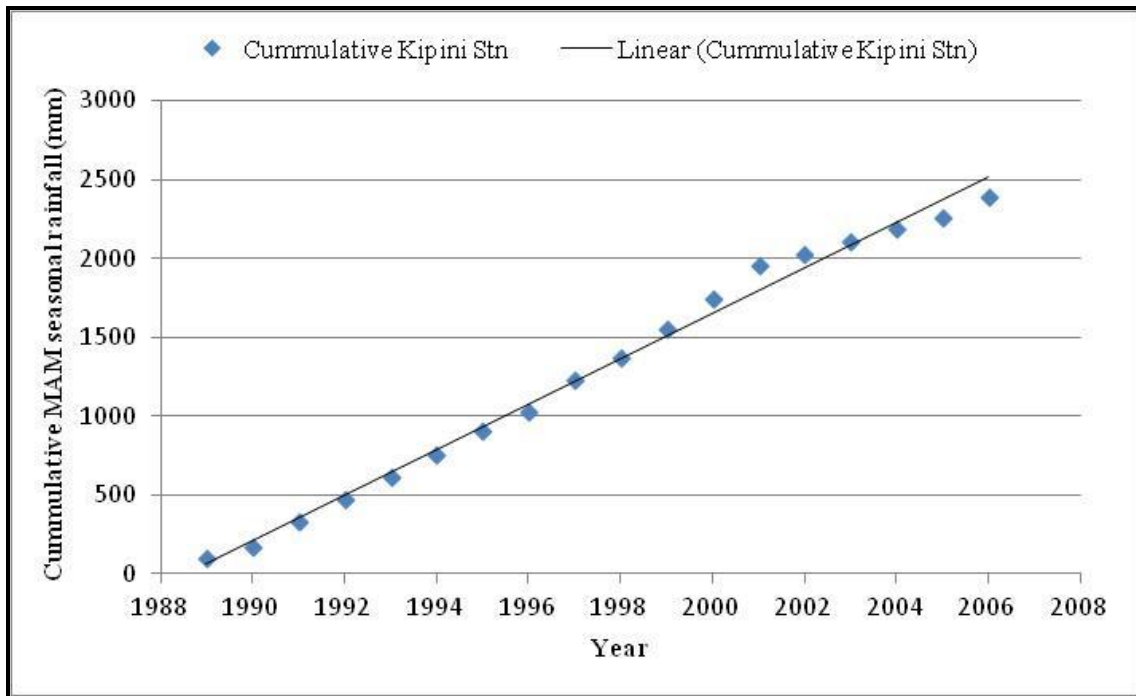


Figure 16: Cumulative single mass curve for MAM seasonal rainfall over Kipini station

Therefore, seasonal rainfall homogeneity tests affirmed that rainfall records obtained from the stations in Tana River County were correctly recorded throughout the years and could be used to infer conclusions regarding the study objectives.

Similarly, the homogeneity tests results for temperature (minimum and maximum) data done using Garissa synoptic station December- February (DJF) minimum temperature data is illustrated in Figure 17. Like in rainfall records, the homogeneity test reveals the consistency in temperature records over time and hence good quality for the study.

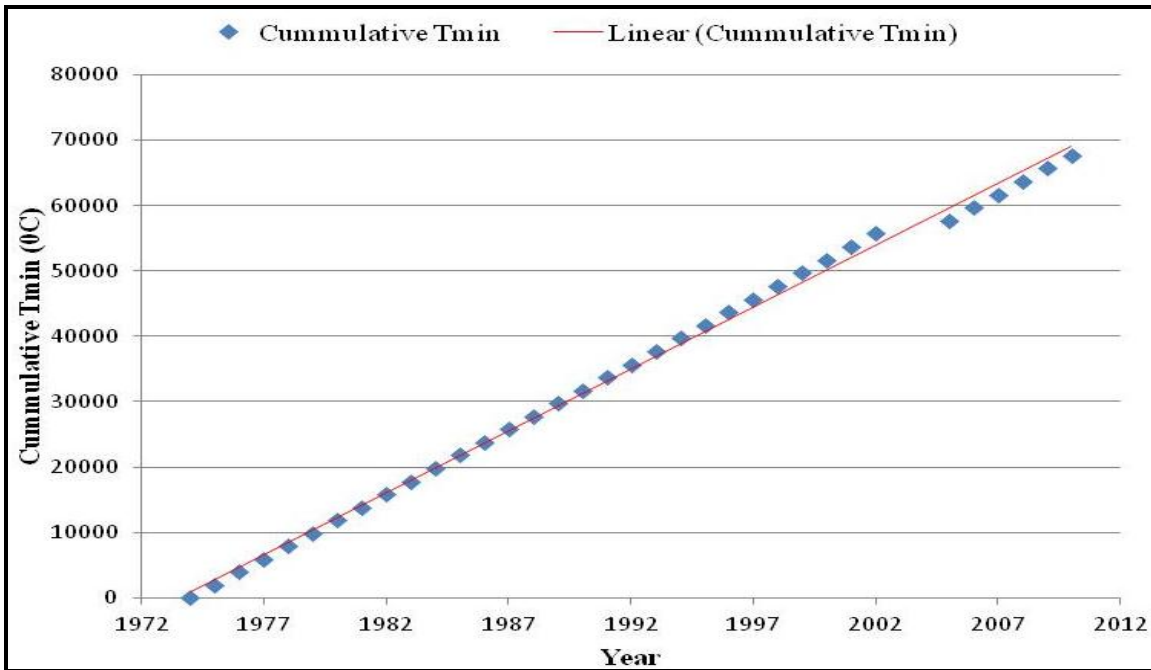


Figure 17: Cumulative single mass curves for January-December mean minimum (T_{\min}) surface temperature over Garissa station

In summary, the quality control analyses for the study climate data affirmed that records were of good quality and appropriate for pursuing the overall and specific study objectives. These results formed the foundation for the study analyses undertaken to investigate the various specific objectives in this study. The next section 4.3.2 presents the results from the characterization of rainfall and mean surface temperature together with their relationships to crop and livestock productions in Tana River County. The section first highlights the status and the distribution network of weather observation points in the region which is critical to understanding Tana River County climatology and its potential threats posed by climate change.

4.3.2 Characterization of climate and relationships to crop and livestock productions in Tana River County

4.3.2.1 Tana River County weather stations

Kenya's agro-meteorological stations are largely located in the high potential zones with very few stations located in the ASALs (Oludhe, 2008). The exploration of weather stations in Tana River County reveals a region with few and sparsely distributed stations (see Figure 4). Majority of these stations were located along the River Tana channel. The few stations in the

region re-affirm the existing reality of large deficits of data observation points in the country (EAC, 2004) as illustrated in Appendix 4 Tana River County has six weather stations namely Garissa, Bura, Tana, Garsen, Witu and Kipini. Five of these stations are rainfall recording stations while Garissa station is the only synoptic station in the region. Similarly, Bura station is the only one located in the low population density area of Tana River County. The location of these weather stations in the region were largely linked to the prioritized economic development zones (i.e. agricultural sector), disaster risks such as floods and lastly a strategic zone for enhancing national/regional meteorological observation network. Details for the six weather stations in Tana River County can be obtained in Appendix 4.

Garissa weather station, as the only major agro-meteorological and synoptic station in the region is classified as grade A and located north of Tana River County (see Figure 4). The station records most of the meteorological variables and considered as a reference station for national, regional and global climate observation network. The station is one of the oldest in the region having been established in 1932. The temperature records from Garissa station was used to understand and explain the temperature scenarios in the Tana River County. Other neighbouring weather stations considered to enhance the regional understanding of climate include Lamu (Lamu County) and Masalani (Ijaara, Garissa County) weather stations. It noteworthy to point out that most of the rainfall recording stations established in the County in late 1970s collapsed in the early 2000s. This was attributed to many institutional challenges associated with sustaining climate data observation points amongst other factors facing the ASAL environment. Consequently, over 80% of the existing weather stations in the region are classified as grade B and focuses mainly on rainfall records. It was also established that volunteer data observers from data partnering organizations were well trained by KMS on the regulations and requirements of rainfall measurement particularly using rain gauges.

To adequately adapt, mitigate and support the adaptation of the agricultural production activities against the vagaries of climate change and variability, KMS had initiated key programmes to increase weather observation points in the region (particularly rainfall records) with the aim of enhancing future climate forecasting in the region and other ASAL areas. These initiatives include the use of local primary schools and other strategic institutions in the region as centres of data observation. However, KMS reliance on other government institutions and community volunteers in weather data collection have its own set-backs and explains the

existence of data discontinuities or non-conformities (data gaps) in most observed data in ASALs. A critical observation of this study was the collapse of most of grade B weather stations in the region which can be associated with the increasing institutional challenges facing the partnering institutions such as staff shortages, transfers, equipment break-downs and inadequate funding to these institutions in ASALs.

4.3.2.2 Annual rainfall variability

The mean annual rainfall in Tana River County varies from 300 mm in Garissa station to slightly above 1100 mm in Witu (Figure 18). Only two stations (Kipini and Witu) in the region receive mean annual rainfall amounts of more than 1000 mm. Similarly, three stations receive mean rainfall of below 500 mm per year (Garissa, Bura and Tana). A normality test using box plots identified that all weather stations except Witu had data outliers. These outliers were largely linked to incorrect measurement or data entry errors. The results show that weather stations have a significant effect on rainfall records with respect to location and variation. Witu and Kipini has the highest rainfall response (above 1000 mm) while the other stations Garissa, Bura, Tana and Garsen have the least variable rainfall responses.

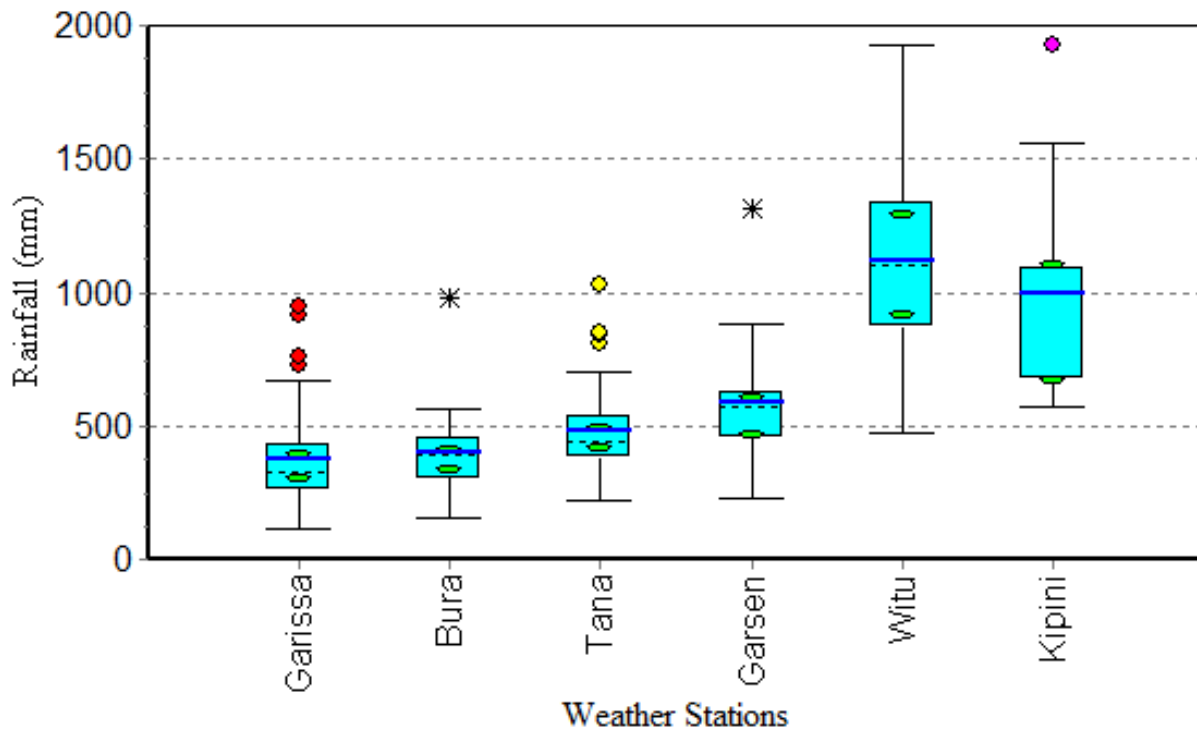
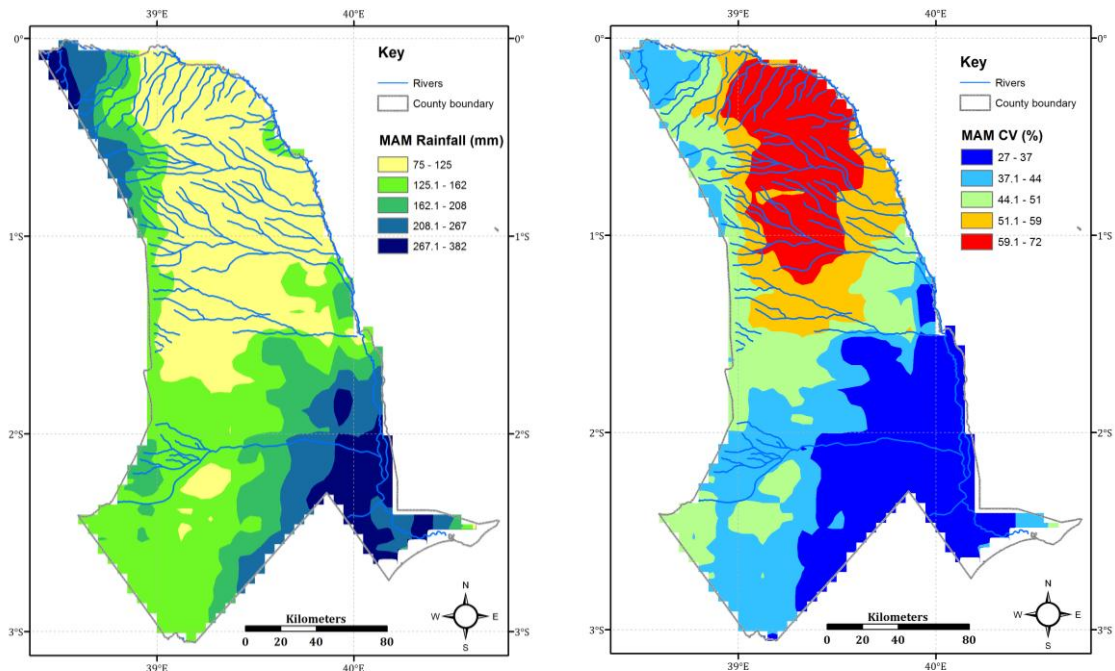


Figure 18: Mean annual rainfall in Tana River County (Source: Author, 2015)

The study demonstrates that Witu and Kipini areas receives the highest mean rainfall in the region and make up excellent agricultural potential zones under rainfed production conditions. These areas are also close to the Indian Ocean and periodically receive convectional rain which further boosts this agricultural potential in the region. Correspondingly, the inter-land areas such as Garissa, Bura and Tana receives depressed annual mean rainfall of below 400 mm (see Figure 18) and poses serious challenges to rainfed agricultural production in the region.

4.3.2.3 *Seasonal and decadal rainfall variability*

Seasonal rainfall in Tana River County is highly variable both during MAM and OND seasons as shown by the coefficients of variations (CV) values (Figures 19 and 20). During the long rains season (MAM), the northern part of the County (Garissa, Bura, Hola) experiences high rainfall variability ranging from 59% to 72% CV as compared to southern part (Kipini and Witu) with CV indexes of 27 to 37 % (Figure 19). The low coefficient of variation values in Kipini and Witu during the MAM season elucidates the reliability of the season for agricultural production activities. These areas are considered food baskets and sources of most agricultural produce to coast and northern Kenya corridor.

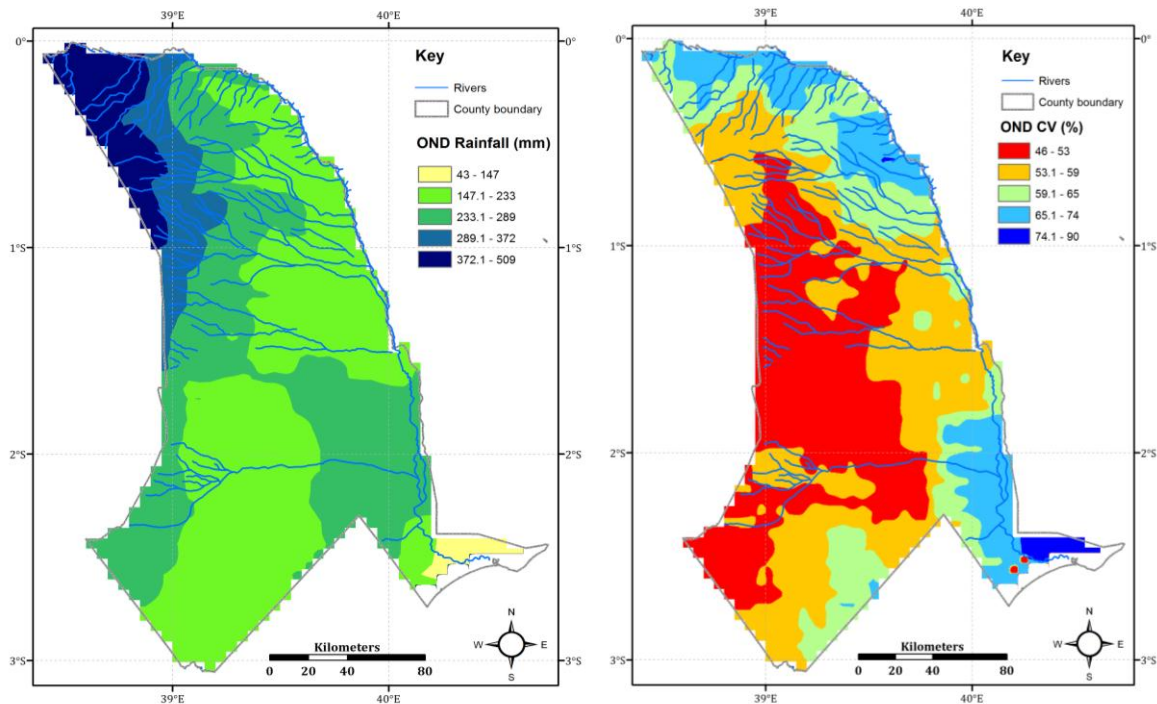


(a) MAM rainfall climatology (1981-2010) (b) Coefficient of Variation (CV) for MAM

Figure 19: Tana River County MAM rainfall characteristics (a) climatology and (b) CVs

(Source: Author, 2016)

Similarly, during the short rains season (OND), high rainfall variability is experienced in the southern Tana River County (Kipini, Witu) with CV indexes going up to 90% (Figure 20). During the season, the eastern part of the County have more reliable rainfall season (lower variability) and usually most relied by the communities. This observation concurs well with IPCC reports that the OND seasons are better relied in the ASALs. These seasonal rainfall variability changes constitute one of key strategic planning information for agricultural managers and policy makers in Tana River County planning various agricultural activities and food security sustainability arrangements. The observed high seasonal rainfall variability affects crop and livestock production activities in the Tana River County. The assessment of such potential risks posed to agricultural production needs to be incorporated in decision making process.



OND rainfall climatology (1981-2010) (b) Coefficient of Variation (CV) for OND

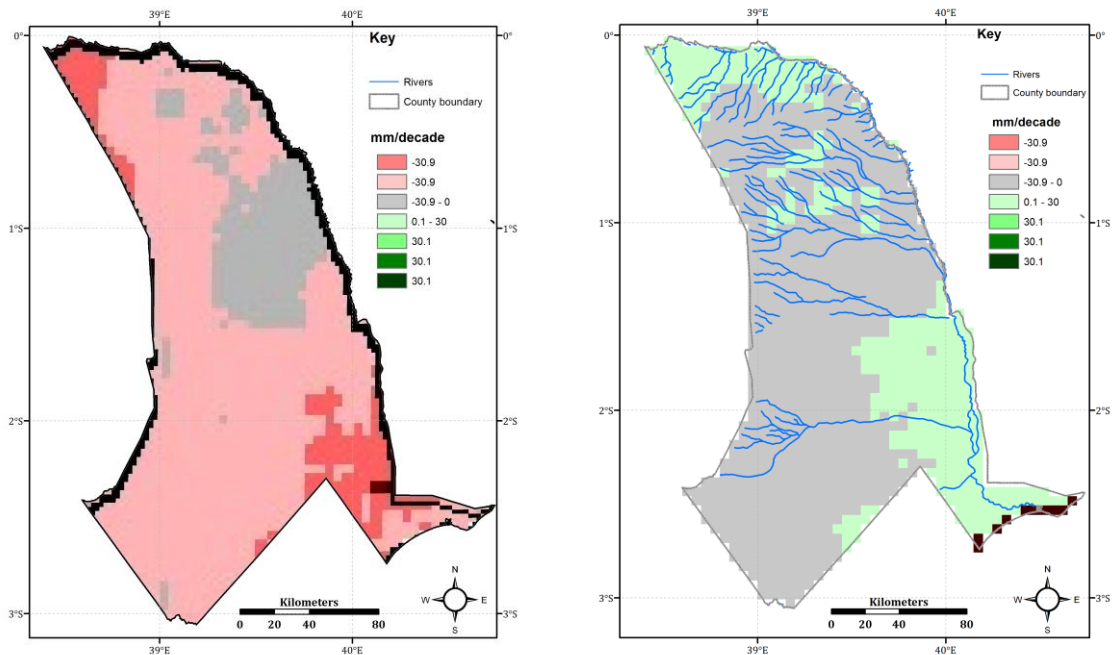
Figure 20: Tana River County OND rainfall characteristics (a) Climatology and (b) CVs

(Source: Author, 2015)

In agricultural planning, the seasonal variability information such as the seasonal mean, intensity and amount distribution is critical in increasing agricultural production. It influences the type of crops and varieties to be planted in the specific sites, the climate change and variability adaptation interventions, disaster risk management to combat loss of livelihood as well as human

lives, and other infrastructural investments. Seasonal variability is the principal source of fluctuations in conventional food production in the eastern Africa and especially in the arid and semi-arid areas such as the Tana River County. Historically, many of the biggest shortfalls in crop production results from drought, caused by anomalous low precipitation in the season (Sivakumar *et al.*, 2005).

Similarly, the decadal seasonal rainfall change reveals decreased rainfall of up to 40 mm/decade in during the MAM season and an increased rainfall of up to 30 mm/decade in the during OND season. Highest increase in the OND seasonal rainfall is observed along the coastline (Kipini, Witu and arissa) as illustrated in Figures 21 (a) and (b) respectively.



(a) March – May (MAM)

(b) October – December (OND)

Figure 21: Decadal seasonal rainfall change in Tana River County for (a) MAM and (b) OND seasons (*Source: Author, 2016*)

4.3.2.4 Mean annual rainfall cycle

The annual rainfall cycle in Tana River County reveals the bimodal rainfall seasons i.e. March - May (MAM) and October-December (OND) with peak rainfall amounts received in April/May and November respectively (see Figure 22). This finding is in agreement with the north – south movement of rainfall band described by the ITCZ and the general rainfall cycle trends within the tropics. The MAM and OND rainfall seasons influences the crop production activities in the region in relation to crop area (area planted), cropping intensity (number of crops planted in the season) and seasonal potential yields. The mean rainfall in the County during the MAM season varies in locations with different implications on the agricultural potential. Kipini and Witu have the highest mean rainfall during the MAM season and this is linked to the good agricultural production observed in the two areas (as illustrate in Figure 22). Similarly, OND season have low mean rainfall values but most reliable for areas in the northern region of the County. A Focused Group Discussion (FGD) affirmed that although OND season have low means and highly variable, it is more reliable in Garissa, Bura, and Tana areas as compared to the MAM season.

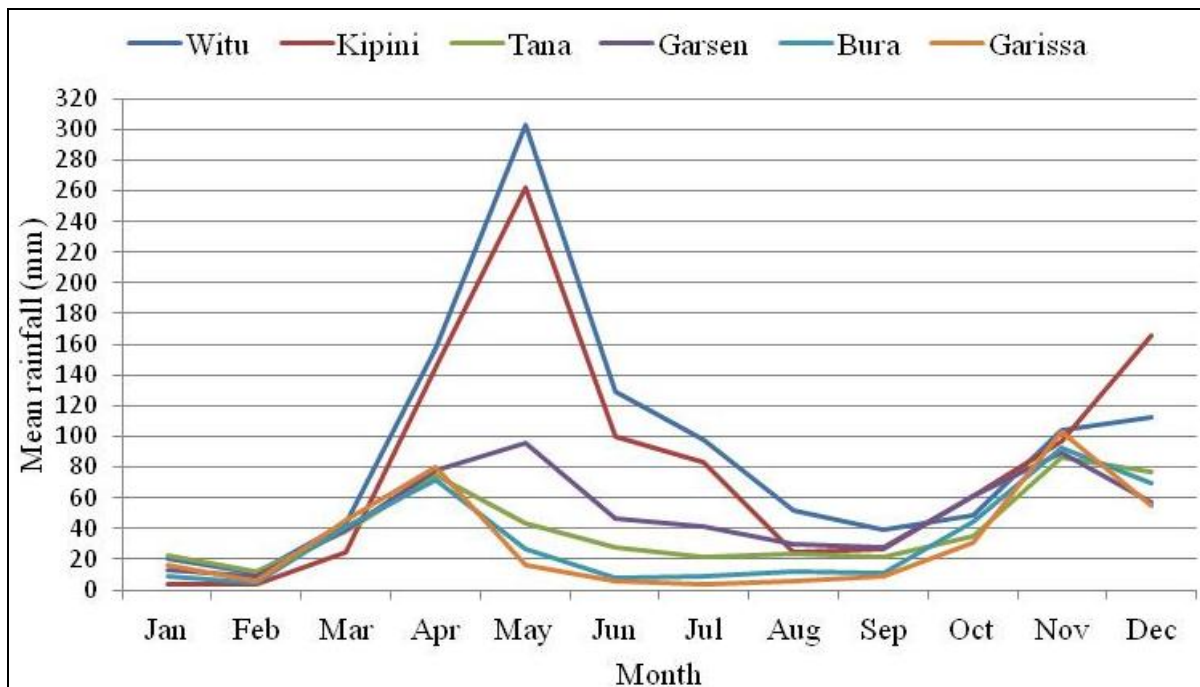


Figure 22: Mean annual rainfall cycle in Tana River County (*Source: Author, 2015*)

4.3.2.5 Inter-annual rainfall variability

Interannual rainfall variation in Tana River County is tightly linked to the regional climate system drivers such as the El Niño Southern Oscillation (ENSO) and IOD that influences its climate system. Analysis of long-term observed rainfall in the region (1951 to 2011) reveals variability and the periodic occurrence of extreme climate events such as floods and drought which are associated with devastating effects on food production and other livelihood sources (Figure 23). Rainfall variability in the region is more pronounced along the southern region (Witu, Kipini and neighbouring Lamu) as compared to the north of Tana River County (Garissa, Bura and Tana). Conspicuously visible is the 1997 above normal rainfall (floods) that had devastating effects to food security and livelihoods in the region.

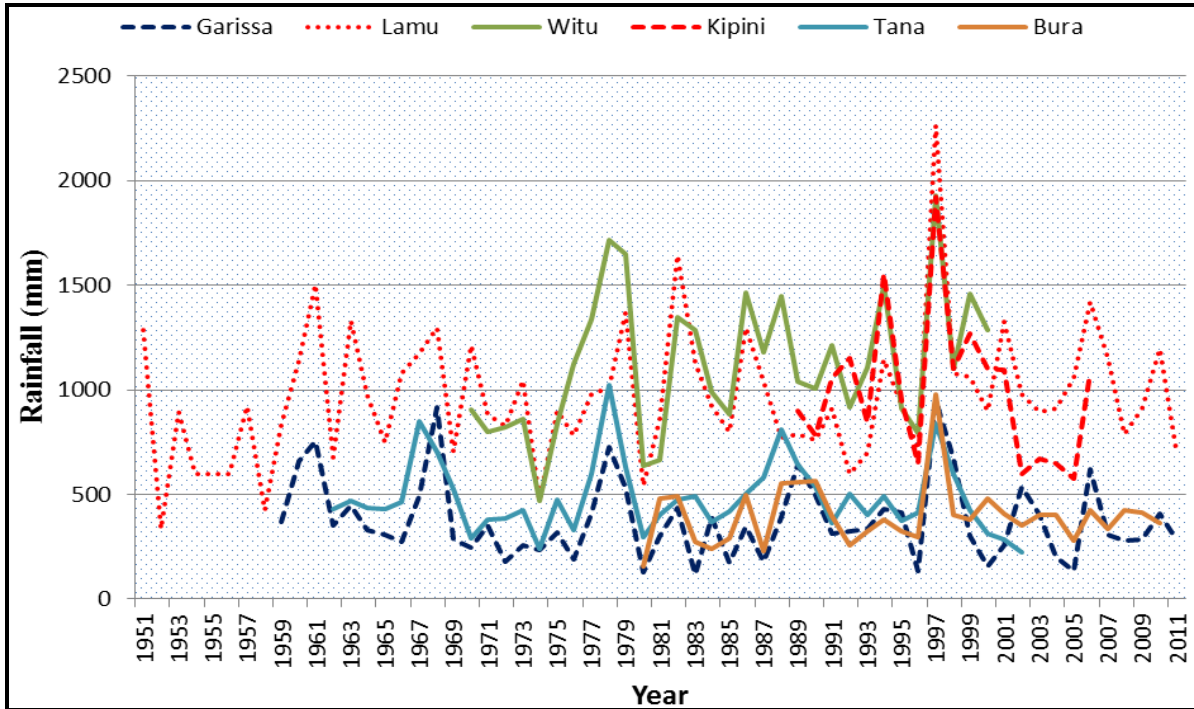


Figure 23: Interannual rainfall variability in Tana River County (Source: Author, 2015)

The number and distribution of total rainy days in the northern region of Tana River County is illustrated in Figure 24. Generally, the number of rainy days in the region is highly variable making rainfed agricultural production activities very difficult. Agricultural production activities such as type of crops cultivated, varieties to be planted and choice of livestock types is adversely affected by such trends and ultimately the food security conditions in the County. This

climatic information from the County provides is critical for agricultural planning including the opportunity to mitigate the potential risks facing the agricultural sector in the region.

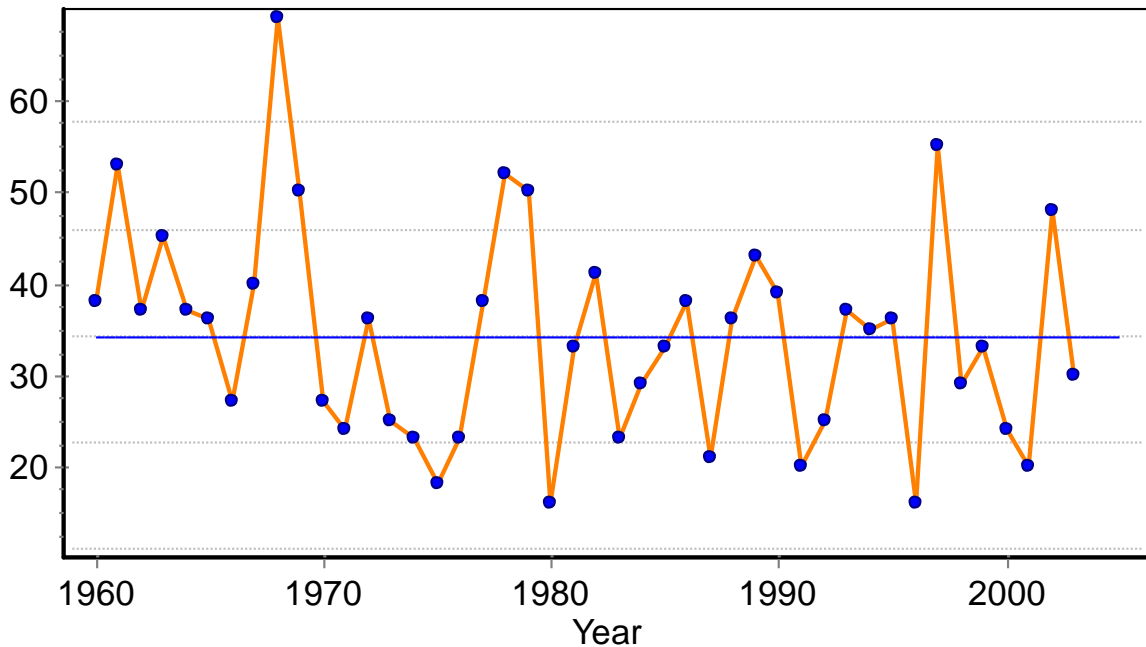


Figure 24: Summary of the number rainy days from Garissa station (*Source: Author, 2015*)

4.3.2.6 *Characterization of extreme climatic events in Tana River County*

Drought and floods are key extreme climatic events that impact agricultural production and other livelihood sources in Tana River County. Agricultural planning can be enhanced if long-term trends of these events are understood and incorporated into decision making process. Analysis of these extreme events in Tana River County using rainfall anomalies reveals the existence of both prolonged depressed and enhanced rainfall events (see Figure 25). The study reveals the return period of above normal mean rainfall (floods) is every 8-10 years while the below normal average rainfall (droughts) is 4 years. Some of the extreme flood related events in Tana River County was experienced during 1997/98 period while the prolonged droughts which led to severe famines was in 1983/84, 1995/96 and 2004/2005 (see Figure 25). The La Niña event of 1999/2001 related drought was widely observed in the entire eastern Africa including Tana River County with negative effects recorded on community livelihood sources. The event aggravated the already existing ASALs conditions in the region, placing more population and communities at risk of starvation (food insecurity) and loss of livelihoods.

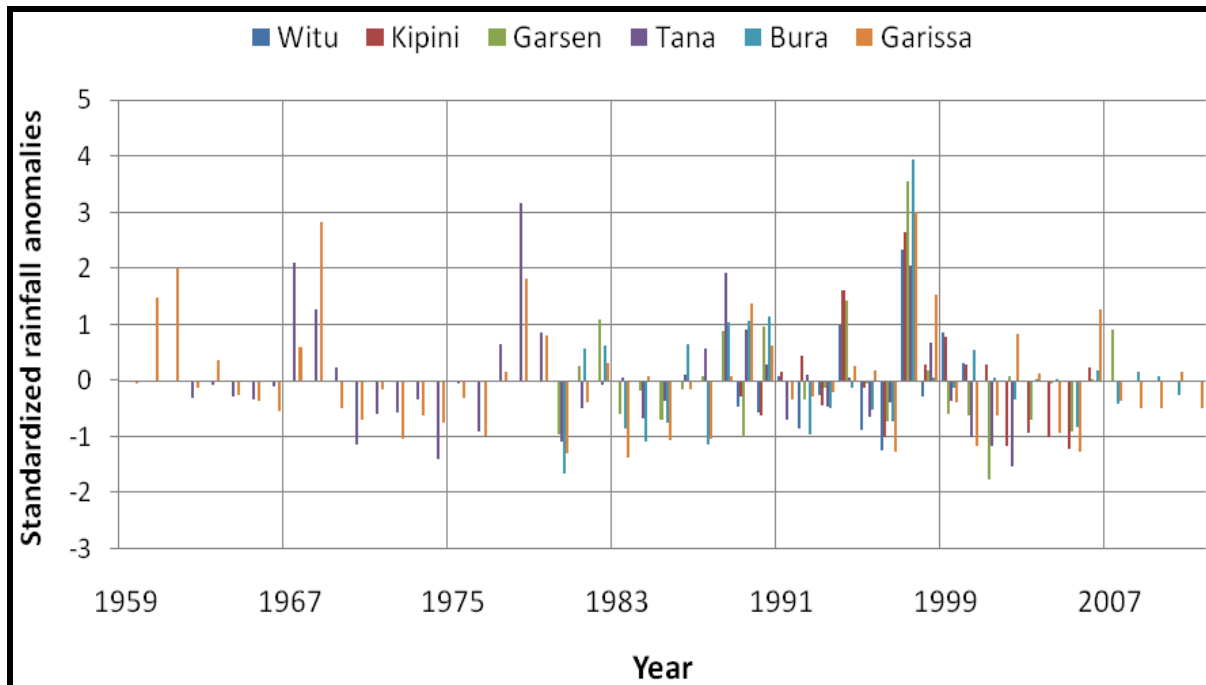


Figure 25: Annual rainfall anomalies in Tana River County (Source: Author, 2015)

The above study finding concurs well with Ojwang’ *et al.* (2010) on the occurrences of extreme events in Kenya which posed many economic development challenges and affected wider population in different parts of the Kenya as illustrated in Appendix 5. Further, Alexander *et al.* (2011) projected that the impact of climatic changes in Kenya that is largely associated with increased occurrences, magnitudes and intensity of such extreme climatic events will cause annual GDP loss of 2 to 3% by 2030 (Appendix 6). This study finding shows that the frequency of drought in the Tana River County has increased and the failure of a rainy season is almost a common event (once every two or three years) rather than the past once in a decade. The increased occurrences of such extreme climatic events require informed planning and decision making in order to minimize their potential impacts. The IPCC AR5 projections on extreme climatic events over the region indicate an increase and therefore, the need to mainstream risk management in policy planning to minimize community vulnerability (IPCC, 2014). The extreme floods often witnessed in River Tana are linked to the intense rainfall occurrences upstream at its source on Mt. Kenya and more often poor management of economic activities that utilizes water from River Tana.

4.3.2.7 Temperature characteristics in Tana River County

Unlike the seasonal rainfall variability in the Tana River County, the mean temperature conditions were relatively homogeneous both during MAM and OND seasons (see Figure 26). The mean seasonal surface temperatures ranged from 27⁰C to 30⁰C with the maximum temperature experienced around Hola region. The County experiences relatively low temperatures of about 25⁰C along its western region.

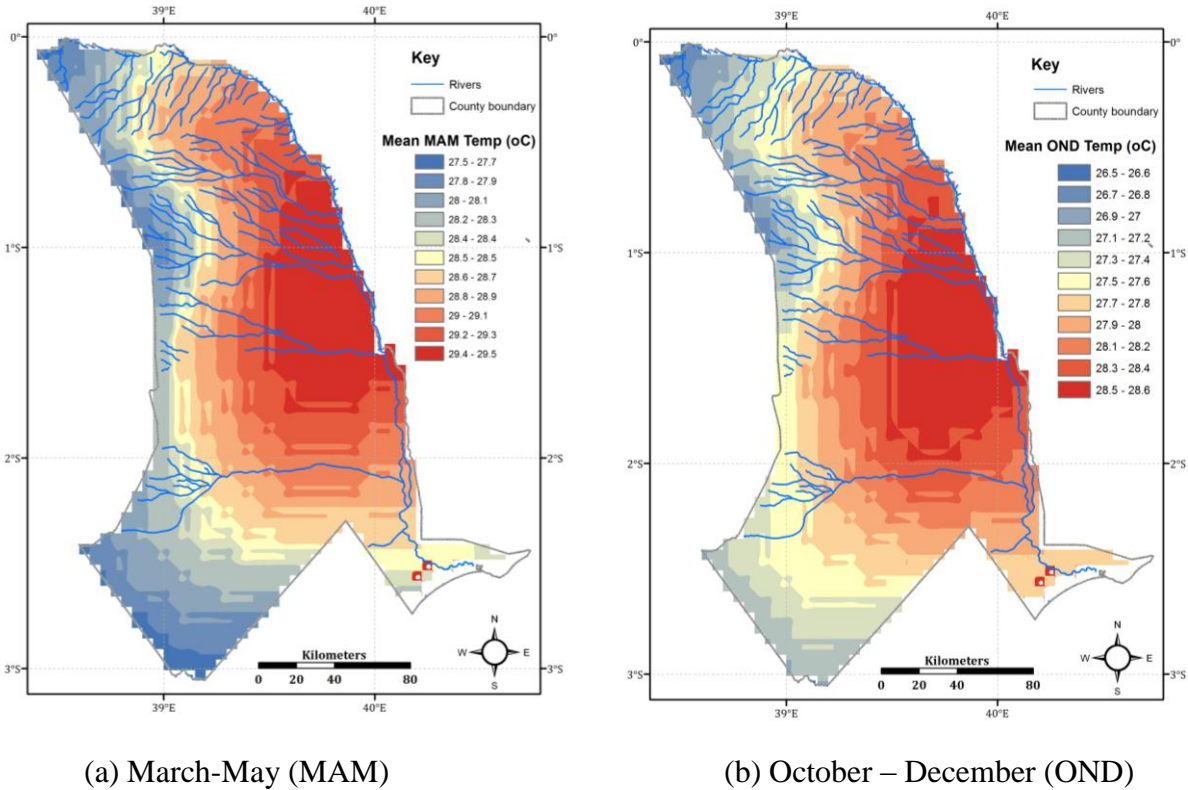


Figure 26: Mean (a) MAM (b) OND seasonal surface temperature (*Source: Author, 2016*)

Further assessment of interannual temperature variability trend indicates a steady increase in both the minimum and maximum mean surface temperatures (see Figure 27). This finding affirms the IPCC temperature projections that the future mean annual temperature (both the minimum and maximum) is expected to increase over the region between 1.0 to 1.5⁰C by 2030. However, more significant increase in the minimum temperature was observed in Tana River County as compared to the maximum temperature (see Figure 27).

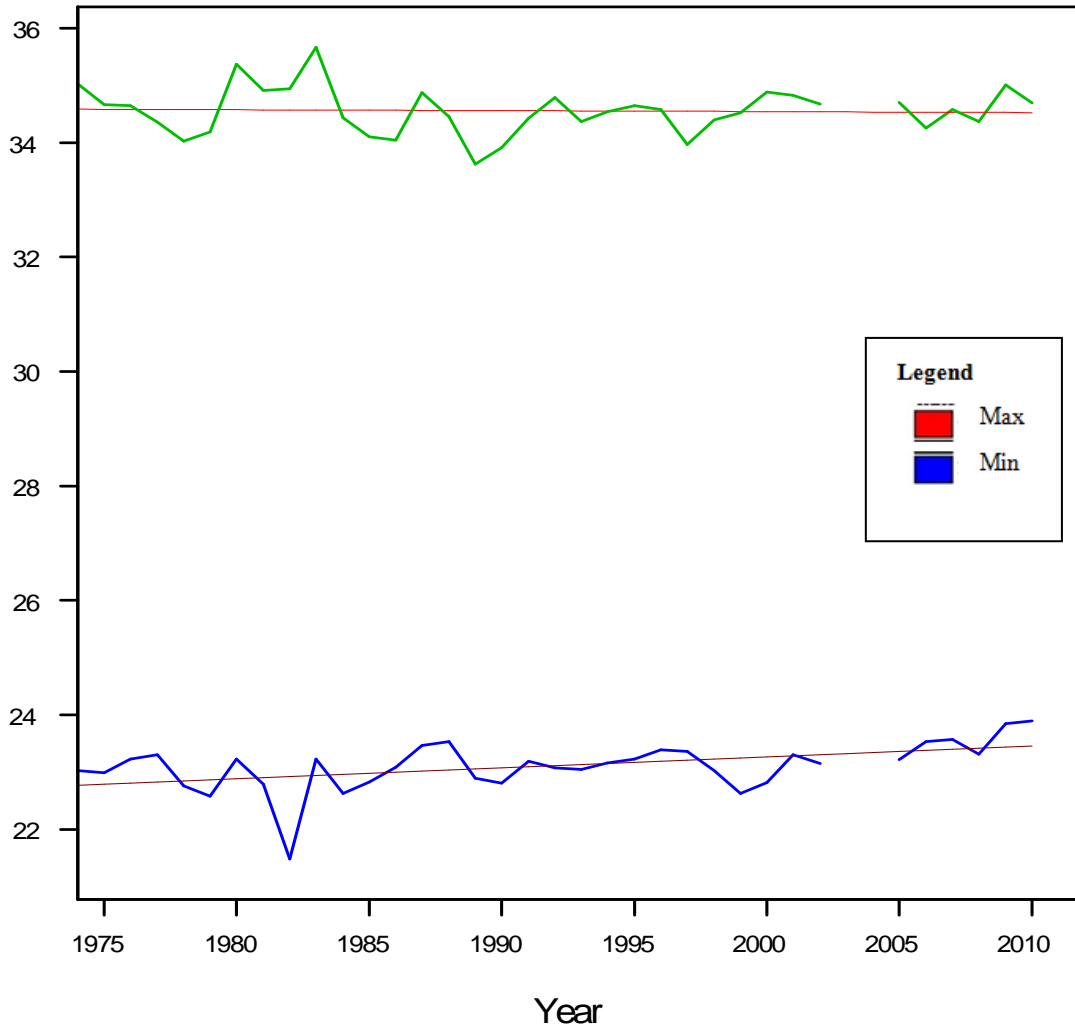


Figure 27: Interannual mean minimum and maximum temperature ($^{\circ}\text{C}$) in Tana River County
(Source: Author, 2016)

The observed increase in both annual and seasonal temperature characteristics in the region poses significant impacts on crop and livestock production activities. Kurukulasuriya *et al.* (2006) reported that the maximum level of temperature is critical in crop production activities and its potential yields especially in the ASALs. The finding points to the existence of a wide and suitable temperature range for optimal crop yields for all types of crops grown in the region and therefore, the impacts of the significant minimum temperature increase on most crops in the region may be negligible. However, the observed increased temperature may increase the percent probability of Tsetse prevalence in the region which will have adverse impacts on livestock production in the region.

4.3.3 Crop production characteristics in Tana River County

Crop production in Tana River County, just like in many other parts of Kenya is highly vulnerable to climate change and variability. Crop production characteristics in the County namely crop types/varieties, yields, variability and relationship with climate were used to influence decisions that relates production and food security.

4.3.3.1 Crop types and yields

Crop diversity and yield potential is central to food security goals of Tana River County. Farmers in the County grow a variety of crops under rain-fed conditions. The widely grown crops across the region were maize, cassava, green grams, rice and mangoes with their mean yields (tons/acre) as 0.6, 6.5, 0.8, 1.4 and 5.2 respectively (see Figure 28). Ketiem *et al.* (2013) reported that the predominantly high yielding crop types in the lower Tana basin such as cassava and mangoes were largely attributed to the individual crop resilience to the changing climate conditions associated with seasonal rainfall variability given that other factors of production are constant. Although maize crop record low yields in the study area, majority of farmers here still prefers it more than cassava and mangoes.

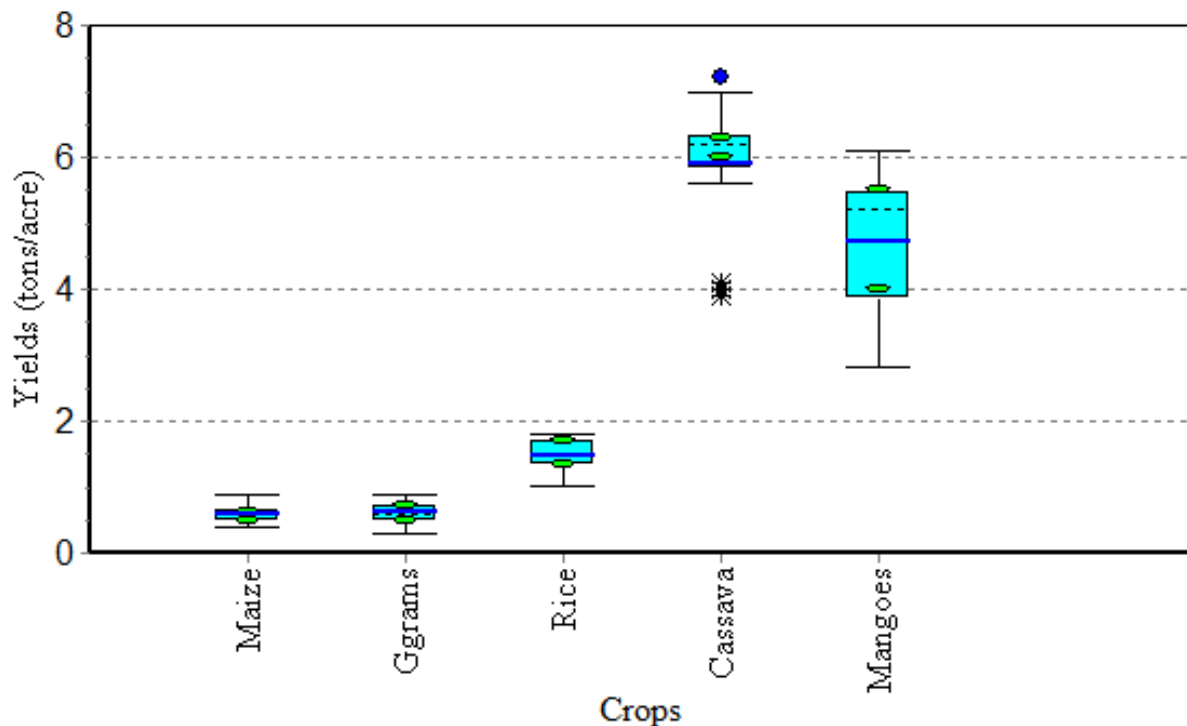


Figure 28: Crop types and yields in Tana River County (Source: Author, 2015)

Crop yields and particularly for the staple food crops is central to the well being of communities in Tana River County. These crops are adversely directly affected by climate and weather conditions. Assessment of widely grown crops under rainfed conditions in Tana River County indicates that most yields were fluctuating as well as declining. Cassava and mangoes yields have consistently demonstrated an increasing trend despite their variability. Yields from Mangoes were at its lowest record of 2.82 tons/acre in the early 90s and have increased significantly to a highest record yield of 6.1 tons/acre by 2010 (approximately 117% increase in 20 years) (see Figure 29). Equally, yields from maize grown in the region within the same period (1990- 2011) recorded the highest yields of 0.9 tons/acre with the trend gradually decreasing to the lowest point of 0.4tons/acre by 2011 (approximately 55% yield decrease in 20 years). Crop yields variation in Tana River County was highest in 1990s as compared to the 2000s period (see Figure 29). The observed non-linearity of inter-annual crop-yields in the region concurs with the findings of Challinor *et al.* (2004) that concluded that the productivity of crops in tropical regions is highly vulnerable to inter-annual and sub-seasonal climate variability

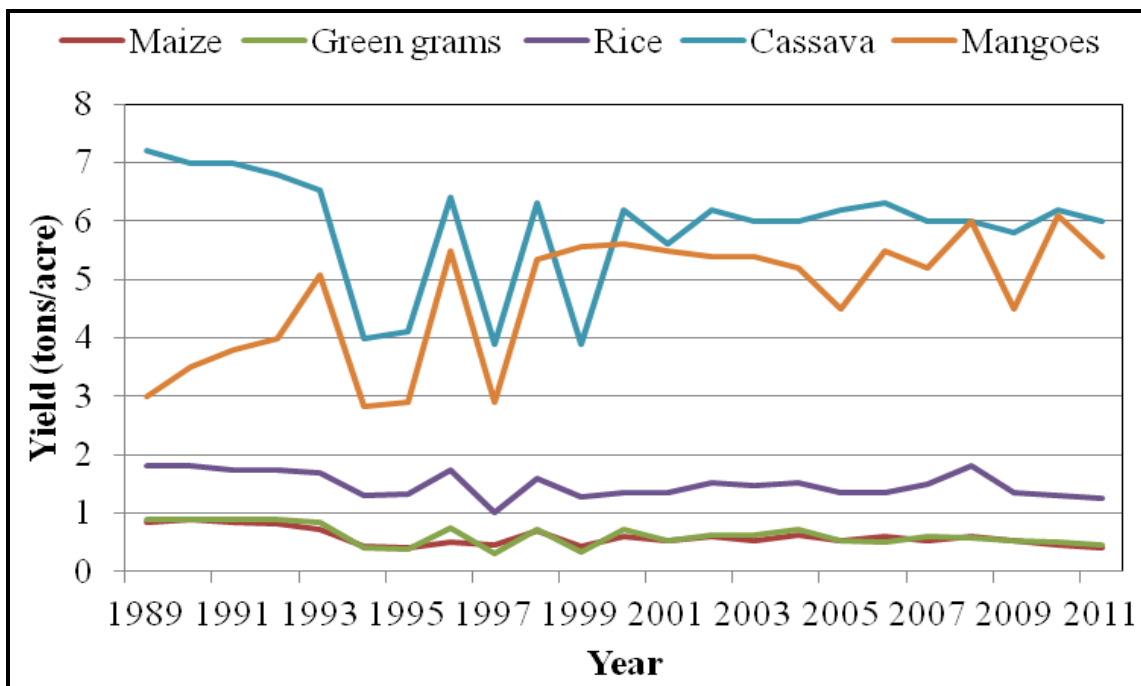


Figure 29: Annual crop yield variability in the lower Tana basin (1989-2011) (Source: Author, 2015)

The impact of the declining crop yields under rainfed conditions in the region remains critical to regional food security strategies and even worst considering the social cultural set ups of most Kenyan communities that considers maize production as the only source to staple food for households. Most of the widely grown crops in the region with exception of cassava and mangoes yielded below their mean values since 2005 (negative anomalies) as illustrated in Figure 30, a clear indication of the serious threat posed to food security of Tana River County. A bumper harvests of rice crop (Figure 30) occurred in 2008 as a result of the heavy rains experienced in 2007 (El Nino) that flooded the rice growing areas.

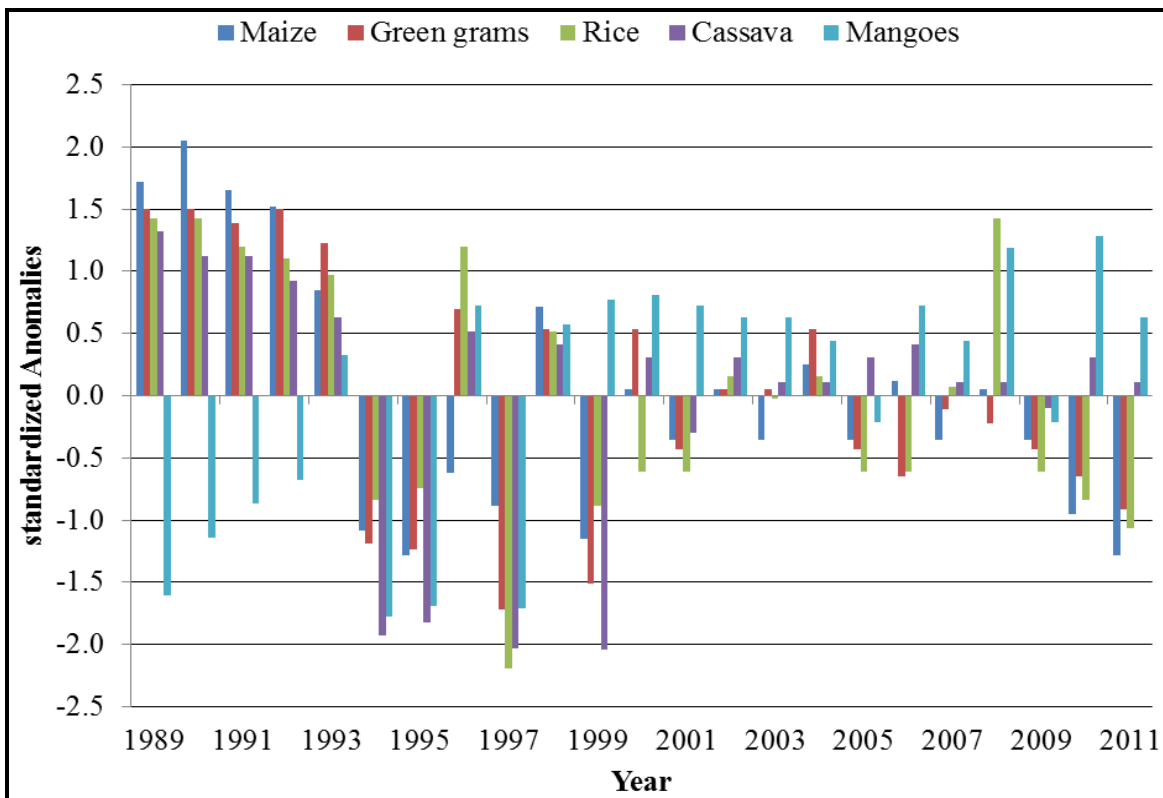


Figure 30: Annual crop yield anomalies in Tana River County (1989-2011) (*Source: Author, 2015*)

Yields from mangoes in Tana River County have undergone significant improvements over time, from the observed negative anomaly in 1990s when most of the yields from crops grown in the region were producing above average to a steady strong positive anomaly after 2000 (see Figure 30). This annual yield performance of the crops may be attributed to the inbuilt individual crop resilience to the changes in climatic conditions among other factors of production such as the availability of high yielding varieties to farmers. Correspondingly, the production of

maize, green grams and rice has consistently decreased significantly with time yielding below their averages (negative anomalies). This trend may be attributed to the increased frequency and intensity of drought events (negative anomalies in seasonal rainfall) in the County. The devastating flood event that occurred in 1997 (extreme positive anomaly of seasonal rainfall) led to the highest crop losses in the region as demonstrated in Figure 30 above and hence widespread food insecurity. These study findings based on analyses of rainfall from weather stations were further re-affirmed during focused group discussion sessions (Appendix 2) where farmers indicated to have observed changes in rainfall seasons and pattern, increased temperature and increased incidences of extreme drought events. In some areas farmers lamented of no more short rains season, delayed rainfall and often start of rains shifted from the usual time. In most of the cases farmers confirmed that delayed rains in the season had resulted in crop failures. Most farmers had also observed changes in the rainfall pattern noting that “rains nowadays *are so unpredictable; it starts late and ends before end of rainy season*”.

In summary, the findings of rainfall and mean surface temperature characteristics from Tana River County reveal a region highly vulnerable to climate change and variability. Similarly, rainfed crop characteristics in the region are significantly impacted with implications on the food security of Tana River County. The declining and highly variable rainfall coupled with upward warming of temperature constitutes key planning information for government agencies, researchers and other development workers in Tana River County so as to strengthen the resilience of communities in the County. Climate change and variability has had adverse effect on maize production and food supply in the maize growing zones of Tana River County (such as Kipini).

4.3.3.2 *Rainfall - crop yield correlations*

The relationship between the MAM and OND seasonal rainfall with seasonal based crop yields (maize and green grams) in Tana River County are illustrated in Table 4. There was a relatively strong negative correlation between maize yield and MAM seasonal rainfall at Kipini (0.45) and a very weak positive relationship at Bura (0.01). Similarly, Garsen had significant negative correlation with green grams (-0.55). In the short rain seasons (OND), Witu had the highest negative correlation of 0.43 with maize (Table 4) as compared to the hinterland areas (Garissa, Bura and Tana) which relies more on the OND season to cultivate crops as earlier

illustrated. This implies that dryland agricultural production need to consider many other production factors beyond rainfall such as soil conservation and crop varieties if higher productivity and food security is to be achieved.

Table 4: Correlation coefficients of maize and green grams yields (tons/kg) with MAM and OND rainfall at six sites in Tana River County

Crop	Season	Witu	Kipini	Garsen	Bura	Tana	Garissa
Maize	MAM	-0.09	-0.45	-0.37	0.01	-0.06	0.23
	OND	-0.43	-0.19	-0.29	-0.09	-0.01	-0.11
Green grams	MAM	-0.03	-0.46	-0.55*	0.03	-0.15	-0.05
	OND	-0.67*	-0.46	-0.49	-0.35	-0.20	-0.36

* Significant correlation

Similarly, green grams and OND rainfall were highly correlated as compared to the MAM season in all the stations with exception of Garsen. The finding concurs with Mburu *et al.* (2014) study results on the effects of climate variability and change on household food sufficiency among small scale farmers of Yatta district in Kenya. It showed that crop yields were mostly negatively correlated in areas where the rainfall coefficients of variations (CV) were high.

Regarding the annual crops such as rice, mangoes and cassava that rely on mean annual rainfall totals to produce, rice and cassava had highest strong negative correlation of 0.81 and 0.68 respectively at Kipini (Table 5). Mangoes yields had some of the highest correlation values at Tana (0.57), Garsen (0.52) and Garissa, suggesting the strong contribution of throughout the year River Tana waters.

Table 5: Correlation coefficients of annual crop yields and mean annual rainfall totals at six sites in Tana River County

	Witu	Kipini	Garsen	Bura	Tana	Garissa
Rice	-0.79*	-0.81*	-0.59*	-0.46	-0.14	-0.28
Cassava	-0.63*	-0.68*	-0.49	-0.25	-0.16	-0.21
Mangoes	-0.22	-0.36	-0.52*	-0.42	-0.57*	-0.52*

*Significant correlation

In general, most crops showed a weak relationship with seasonal rainfall in the hinterland areas except for Mangoes that are grown along River Tana and enjoys throughout the year access to water including the floods. The relatively low correlation coefficients in the hinterland areas explain why measured weather station rainfall is not a good parameter for soil- crop-water relations. There is need to utilize the effective rainfall (energy budgets) to understands their relationships. This result highlights the future research gap which was outside scope of study. The finding therefore rejects the study’s null hypothesis that no statistically significant relationship exist between the seasonal rainfall and crop yields under rainfed conditions in Tana River County and hence the need to also consider the crop energy budgets in future studies before making recommendations for agricultural planning. A regression analyses conducted to ascertain the magnitude at which the independent variable (rainfall) explains the dependent variable (crop yields).

Regression and correlation analysis of maize yields and MAM rainfall for Kipini under rainfed illustrates the low contribution of measured weather station data on yields (Figure 31). Only 8 % of maize variance can be explained by the MAM seasonal rainfall. Further investigation using the energy balances (soil-crop-water relations) is recommended to ascertain this finding.

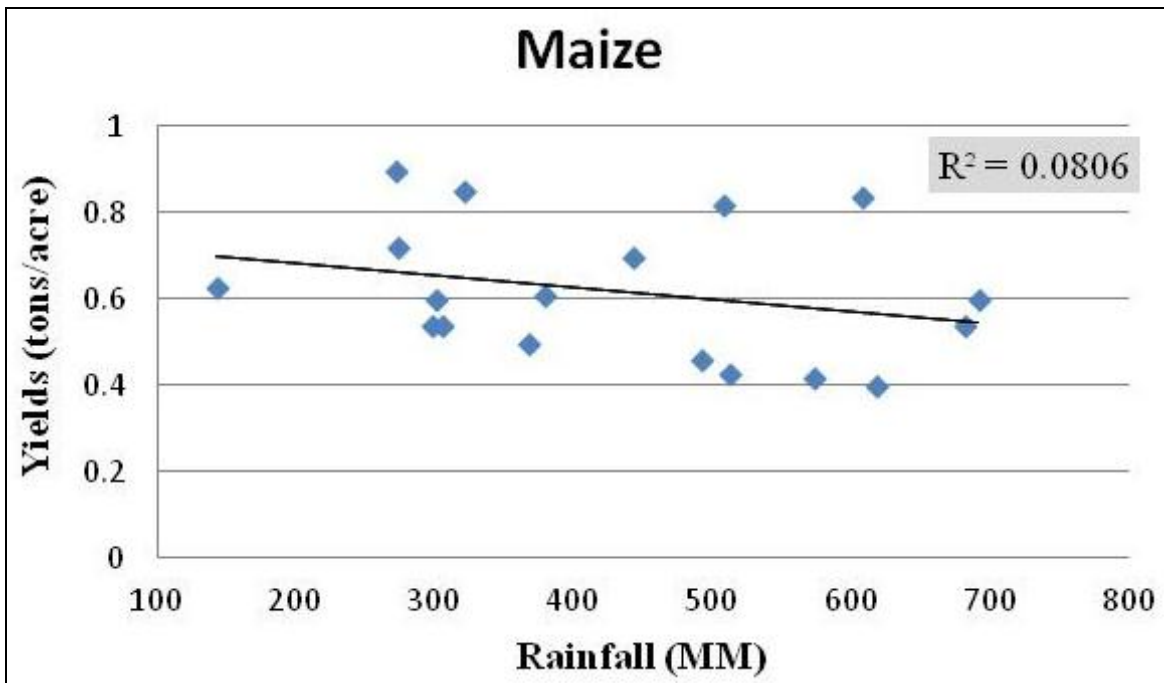


Figure 31: Regression between maize yields and MAM rainfall at Kipini (Source: Author, 2015)

The study hypothesized that higher crop yields (such as maize) in the region were not significantly determined by rainfall alone but an aggregation of other factors. The regression analysis computed for maize showed a coefficient of determination of 0.08 for the MAM rainfall at Kipini. This indicates that only 8% of the variance in maize yields is explained by the seasonal rainfall (see Figure 31). This implies that 92 % of the variance in maize yields at Kipini area (one of the maize potential zones) is explained by other omitted factors not included in the study. The result explains why measured weather station data cannot be used as a parameter for correlation with crop yields. This calls for further investigation using the energy budgets; soil-crop-water relations analysis. The study reveals the significant contribution of other factors other than seasonal rainfall in increased maize yields in the area and need consideration during agricultural planning for the achievement of future food security in the region. Similarly, a regression analysis of green grams and OND seasonal rainfall in Witu which had the highest negative correlation value of 0.67 indicates that only 55% of the variance in green grams yields is explained by the seasonal rainfall (see Figure 32).

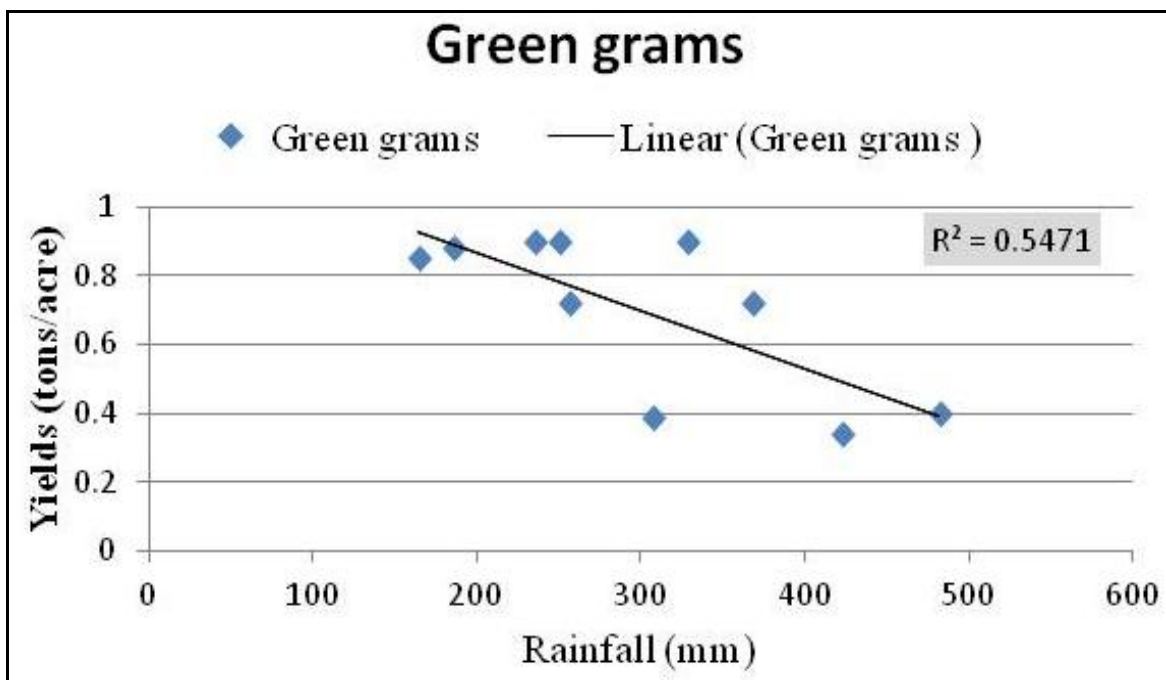


Figure 32: Regression between green grams yields and OND rainfall at Witu (Source: Author, 2015)

Regarding the strong negative correlation of rice yields with annual rainfall totals at Kipini ($r = 0.81$), about 65 percent of rice yields produced in the area is attributed to seasonal rainfall. This explains why rice production is grown in areas closer to Indian ocean receiving high rainfall amounts including the convectional rains.

4.3.3.3 *Livestock production characteristics in Tana River County*

Livestock production in Tana River County is an important component of the farming systems and constitutes the mainstay of livelihoods for majority of communities. The production is largely under nomadic pastoral system. This study assessed the livestock characteristics in the region as influenced by climate variables studied.

4.3.3.3.1 *Type of livestock*

Most pastoralists in the basin keep large herds of livestock such as camels, cattle, goats (Alpine and Galla) and sheep (black head and Persian) (Plate 3) as a means of earning livelihood and spreading the potential risks posed by the adverse impacts of climate change. Some of the major problems facing the pastoralists in the region which are associated with climatic changes include water-scarcity, feed-scarcity and diseases.



Plate 3: Livestock diversity in the lower Tana basin

Fish production though minimal, is also practised at some sites of River Tana, oxbow lakes formed along the River Tana and along 76 km coastline of Indian Ocean. However, the production is challenged by occasional change of river course, drying up of oxbow lakes and presence of crocodiles that poses danger to fishermen.

4.3.3.3.2 Livestock population

In the lower Tana basin, intensive livestock production is practiced in the hinterland areas of the County namely Garsen, Bura, Hola and Madogo. Although these areas receives low (mean of less than 400 mm per annum) and highly erratic rainfall, the existence of expansive grazing fields provides favourable conditions for rearing large herds of livestock and reduces frequent conflicts with sedentary farmers and large scale irrigation firms such as Tana River Development Authority (TARDA) located along River Tana flood plains. These hinterland livestock production areas are characterized by limited pastures and water points that are highly susceptible to climatic changes (prolonged droughts); hence, pastoralists often lose many livestock during drought. The major communities practicing pure pastoralism for livelihood in the region in the region are the Orma and Wardei sub-tribes. A general decreasing trend in livestock population was observed up to 2010. However, goats' population was annually highest as compared to other livestock types kept by pastoralists in the region (see Figure 33).

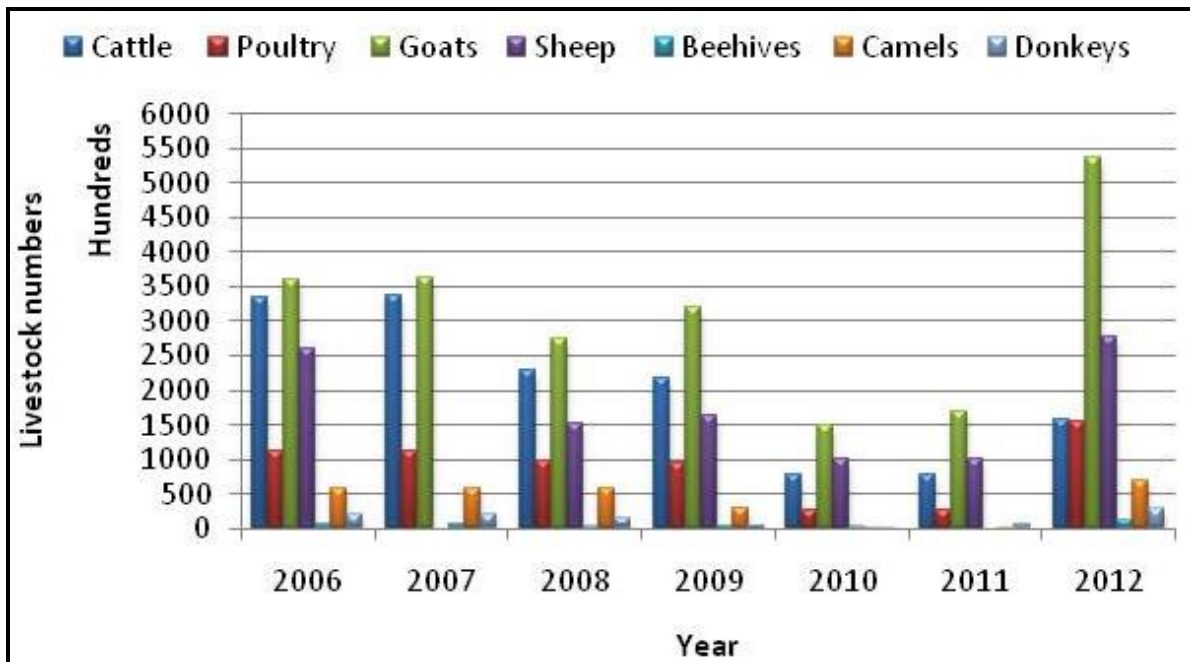


Figure 33: Livestock population trend in the lower Tana (Source: Author, 2015)

The significant increase in goats' population (recording slightly above half a billion in 2012) and more so sheep from 2010 may be associated with the resilience of these livestock types to weather variability and other ASALs limitations. Pastoralists are shifting to more climate resilient livestock types (such as goats, sheep and camels), which can survive adverse climatic conditions associated with pasture limitation, water scarcity and increased diseases. Further, goats have shown the added advantage of browsing the ever green vegetation along River Tana, implying more feeds for goats and hence their increasing numbers.

4.3.3.3.3 *Rainfall- livestock production correlations*

The relationship between the mean annual rainfall and livestock population of major livestock types kept by the pastoralists were positive. In Garissa for example the correlation values for goats, sheep and cattle were 0.26, 0.75 and 0.36 respectively. Similarly in Bura, the correlation values were 0.20, 0.76 and 0.11 respectively. The study showed that sheep production was strongly correlated with rainfall in all the study areas. This finding is linked to the fact that sheep purely relies on pastures as feeds as compared to goats that alternatively browses vegetation. A regression analysis on sheep production in Garissa revealed that only 56% increase in sheep population are explained by rainfall received in the area as illustrated in Table 6.

Table 6: Regression analysis of sheep population changes and rainfall in Garissa

Multiple R	0.75				
R Square	0.56				
Adjusted R Square	0.41				
Observations	5				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	9.5E+09	9.5E+09	3.82704	0.14537898
Residual	3	7.4E+09	2.5E+09		
Total	4	1.7E+10			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>
Intercept	30586.5	67418.4	0.45368	0.68087	-183968.77
X Variable 1	332.462	169.946	1.95628	0.14538	-208.38149

There was a strong relationship between rainfall variability and livestock performance indicators (such as herd population or numbers), suggesting that improved livestock management strategies is necessary to protect the loss of livestock during droughts and minimize the negative impacts of the variable environmental conditions on livestock population. The study recommends for strong linkage between indigenous drought management strategies that incorporate early warning systems and risk management.

4.4 Projected climate change scenarios in Tana River County

4.4.1 Introduction

This section presents the results of projected rainfall and temperature scenarios using ensemble (average) of CORDEX RCMs, the implications on agricultural production and some of the proposed adaptation and mitigation measures suitable for interventions in the lower Tana River basin. An ensemble of the RCMs represented better (than individual single RCM) the topographical details, coastlines and land-surface heterogeneities, and hence more realistically reproduce small-scale processes and details that are essential in developing reliable climate change impact assessment and adaptation policies (Nikulin *et al.*, 2012; Villegas *et al.*, 2013; Edstrom *et al.*, 2015). The proposed implications will guide policy makers and other related resource in the County to formulate appropriate development programmes resilient to the projected climatic changes in the region. Future projections within the scope of this study the IPCC RCP 2.6, RCP4.5 and RCP 8.5 climate change scenarios. The anomalies were taken on a base period of 1971-2000.

4.4.2 Projected rainfall changes over eastern Africa and Tana River County

Figures 34-36 below shows the spatial projected rainfall changes over the eastern Africa region and Tana River County (in grid box) using ensemble RCM based on the RCP 2.6, RCP 4.5 and RCP 8.5 scenarios for the three major seasons during 2030s, 2050s and 2070s with baseline period of 1971-2000.

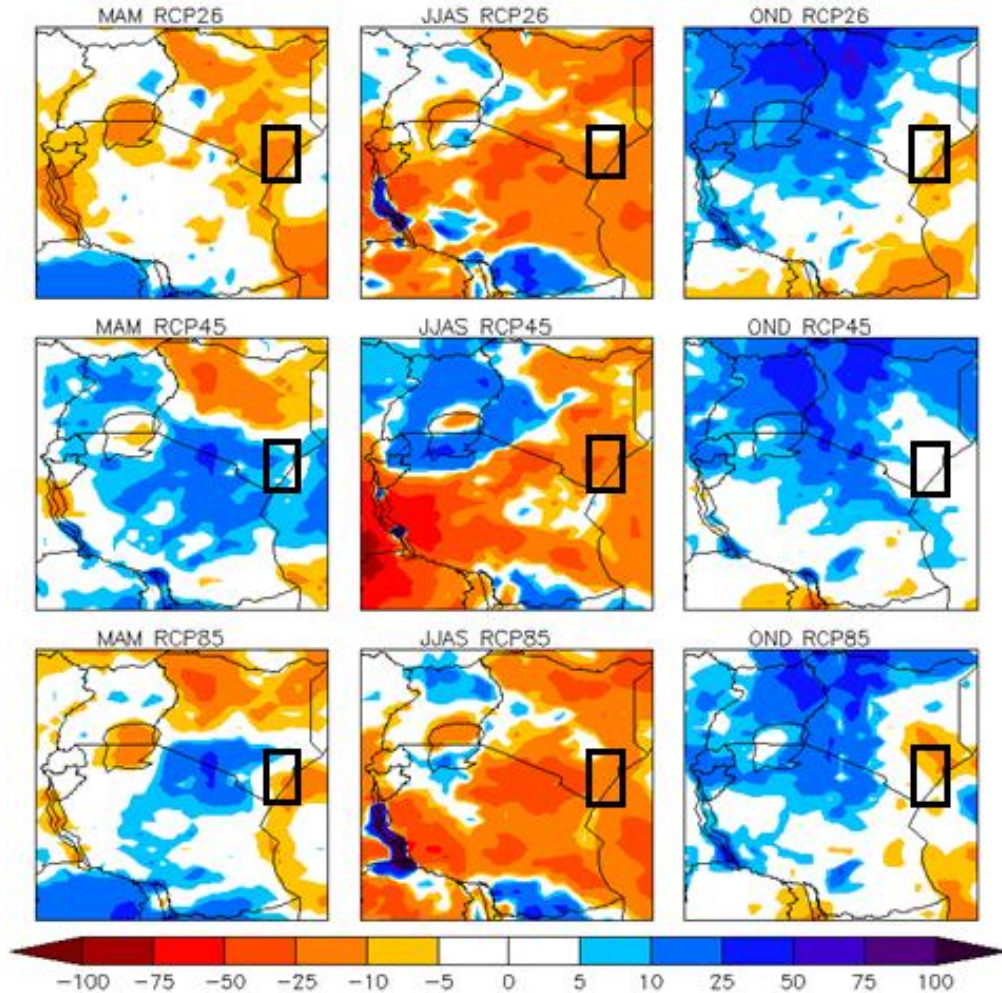


Figure 34: Projected rainfall changes over eastern Africa region and Lower Tana basin (in box) by 2030 in MAM (1st column), JJAS (2nd column), and OND (3rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1st row), RCP4.5 (2nd row) and RCP8.5 (3rd) respectively.

The projected rainfall changes show relatively little change as compared to the baseline period. The short rains (OND period) are projected to increase over the basin under all the three scenarios especially towards 2070 (5-25% by 2030 and 25-50% by 2050 and 2070 respectively). By contrast, generally the long rains (MAM period) are projected to decrease over the study area. The June - September (JJAS) season, when the Coastal region receives some substantial amount of rainfall, is projected to decrease (25-50% 2030 and 50-75% by 2050 and 2070 respectively).

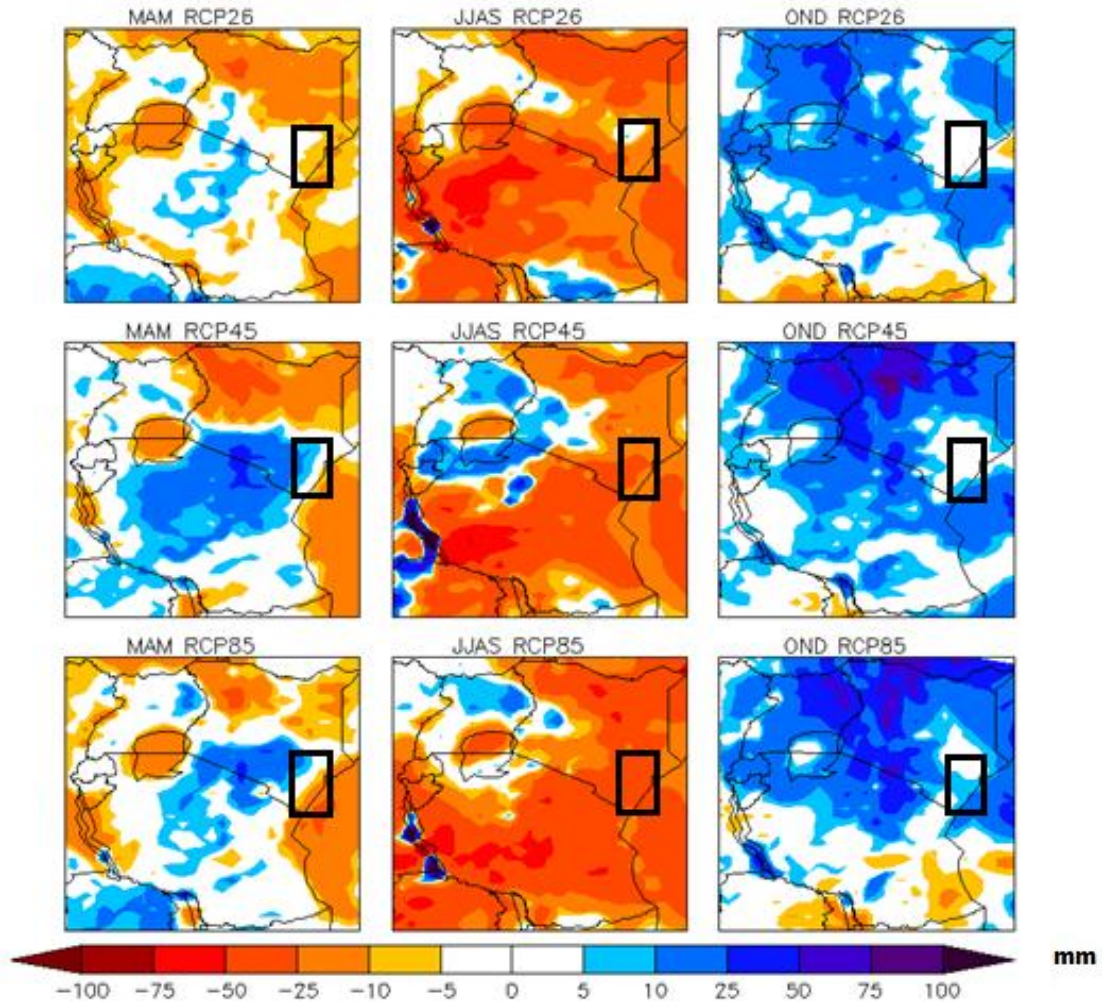


Figure 35: Projected rainfall changes over eastern Africa region and Lower Tana basin (in box) by 2050 in MAM (1st column), JJAS (2nd column), and OND (3rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1st row), RCP4.5 (2nd row) and RCP8.5 (3rd row) respectively.

These rainfall projection results over the eastern Africa region are consistent with the findings reported by Shongwe *et al* (2011) and Anyah and Qiu (2012). In both studies, different models give indications for an increase in mean precipitation rates and intensity of high rainfall events over eastern Africa.

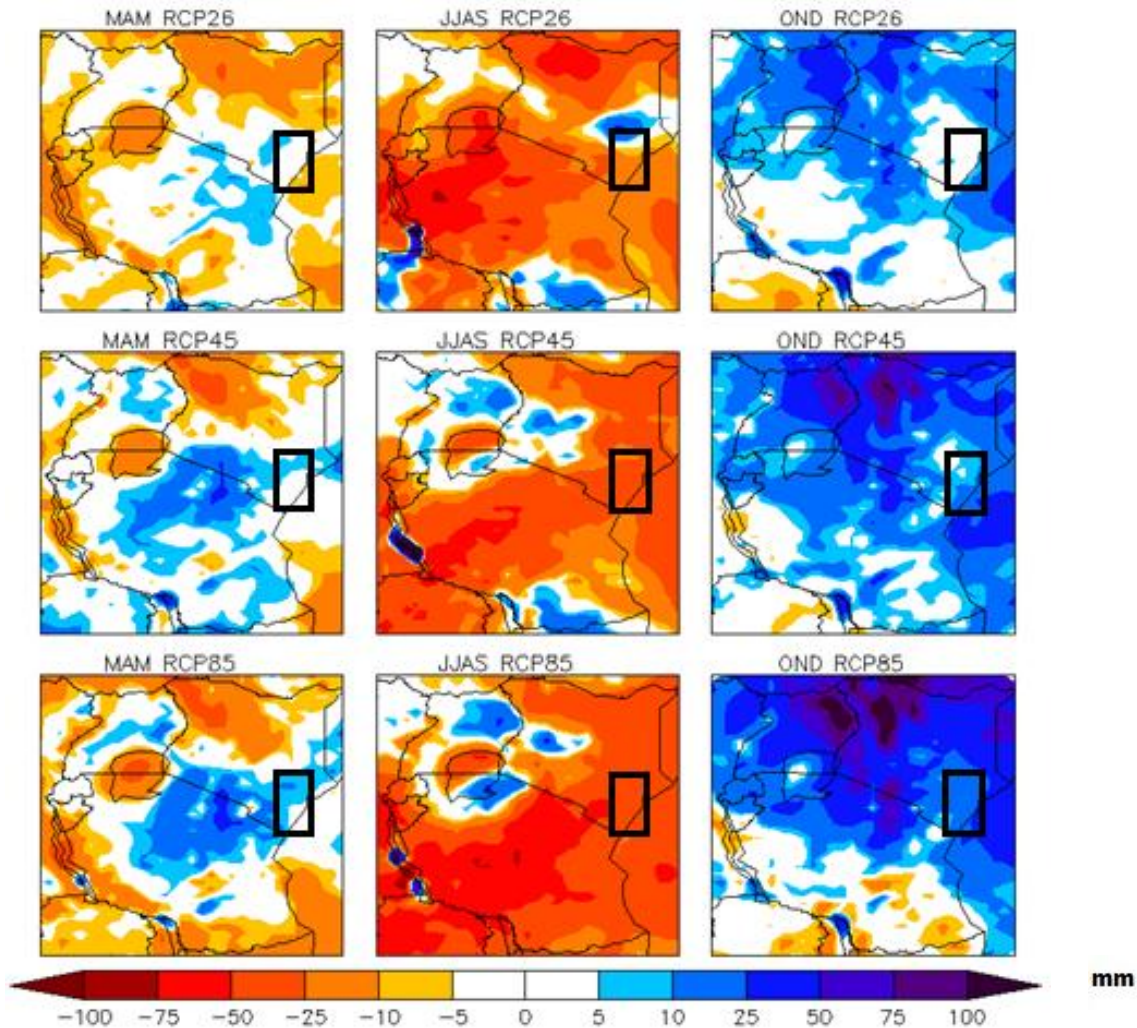


Figure 36: Projected rainfall changes over eastern Africa region and Lower Tana basin (in box) by 2070 in MAM (1st column), JJAS (2nd column), and OND (3rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1st row), RCP4.5 (2nd row) and RCP8.5 (3rd row) respectively.

The results of temporal projected rainfall changes in Tana River County under RCP 4.5 and RCP 8.5 scenarios during the two main crop growing seasons of MAM and OND is depicted by Figure 37. The projected changes reveal insignificant positive precipitation change relative to the base period (1971-2000). The findings shows an increased mean rainfall in 2030, 2050 and 2070 as compared to the baseline period. This finding implies that the basin is projected to get wetter during the MAM and OND seasons by the end of 21st century. However, it is noteworthy

that the cumulative projected rainfall increases in the basin are so small compared to warming observed and that the net effect will be negligible and thus the need to mainstream suitable adaptation and mitigation measures especially in the agricultural production practices.

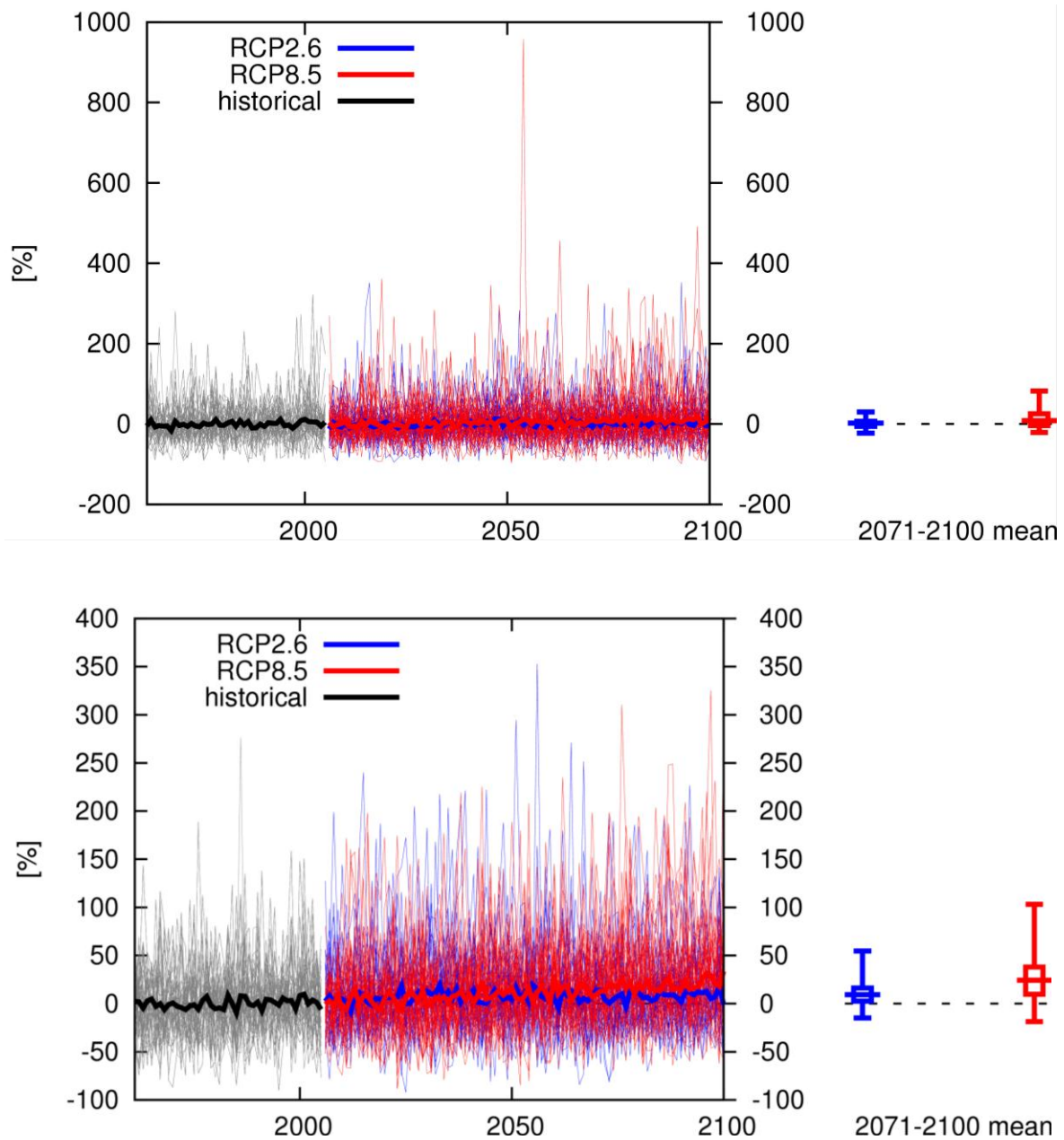


Figure 37: The projected relative precipitation change for MAM (top panel) and OND (bottom panel) over Tana River County (baseline 1971-2000) under RCP 2.6 and RCP 8.5 climate scenarios.

On the left, for each scenario one line per model is shown plus the multi-model mean, on the right percentiles of the whole dataset: the box extends from 25% to 75%, the whiskers from 5% to 95% and the horizontal line denotes the median (50%).

These temporal projected rainfall changes in the lower Tana basin as illustrated in Figure 37 above concurs well with Shongwe *et al.* (2009) and Christensen *et al.* (2007) findings which indicated that the projected global rainfall changes in the tropics and sub-tropics region will increase and decrease respectively. Further, the IPCC AR4 projections also reported that tropical Africa region could have an annual increase in mean rainfall and that eastern Africa region will be wetter as compared to other regions in Africa (Christensen *et al.*, 2007).

4.4.3 Projected temperature changes over eastern Africa and Tana River County

4.4.3.1 Projected maximum temperature change

Figures 38 and 39 below illustrate the projected change in the maximum temperature component for the three scenarios (RCP2.6, RCP4.5 and RCP8.5 respectively) by 2030 period as compared to the reference period (1971–2000). Unlike for rainfall, the projected seasonal temperature changes under the three different scenarios and same time frame show relatively significant increase by the end of the 21st century.

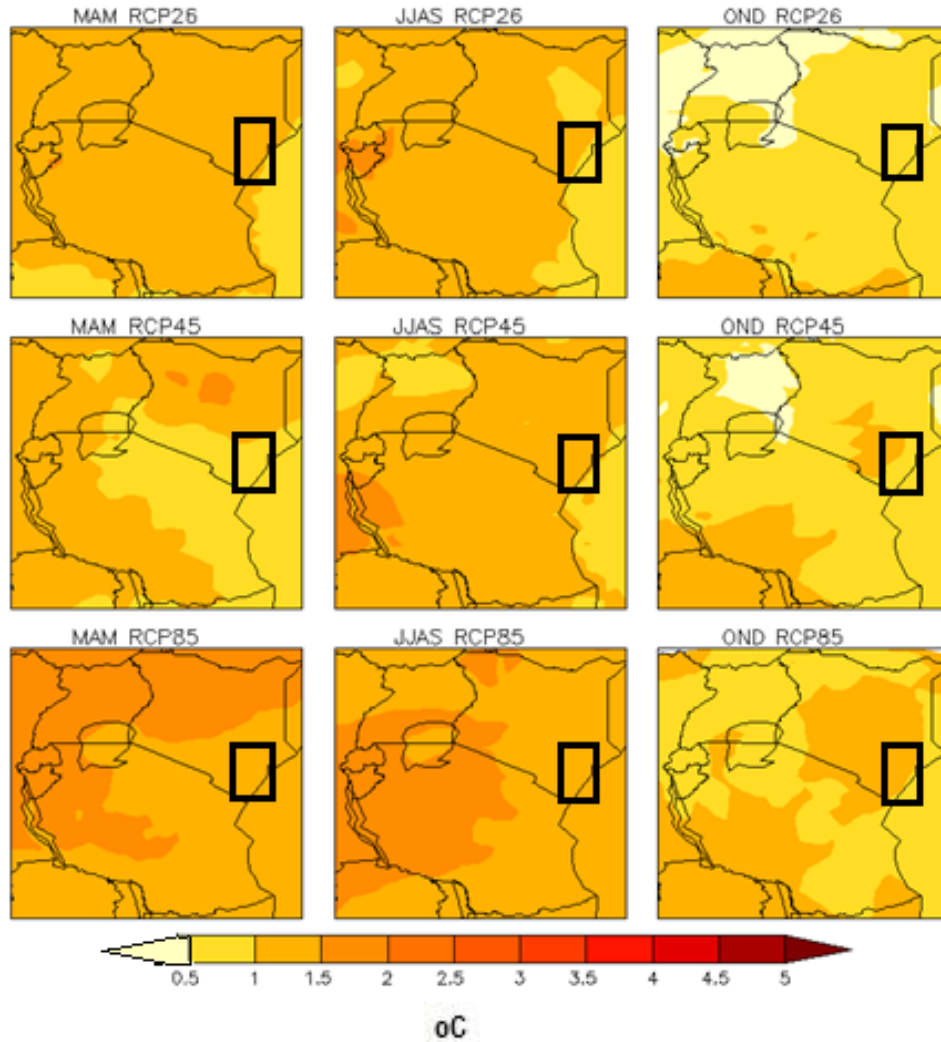


Figure 38: Projected maximum temperature changes over eastern Africa and Tana River County (in grid box) by 2030s in MAM (1st column), JJAS (2nd column), and OND (3rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1st row), RCP4.5 (2nd row) and RCP8.5 (3rd row) respectively.

By 2030 (Figure 38), mean maximum temperatures are anticipated to be 0.5 to 1.0 °C higher under the RCP2.6, RCP4.5 and RCP8.5 scenarios over most parts of eastern Africa and Tana River County. By 2050 (Figure 39), maximum temperatures during the long rains (MAM), the dry season (JJAS) and during short rainy season (OND) will likely increase by 1.0 to 2.0°C over most parts of the region but with spatial variation similar to those for 2030. The expected warming extent is greatest during the long rains (MAM) and the dry season (JJAS) and least during the short rains (OND).

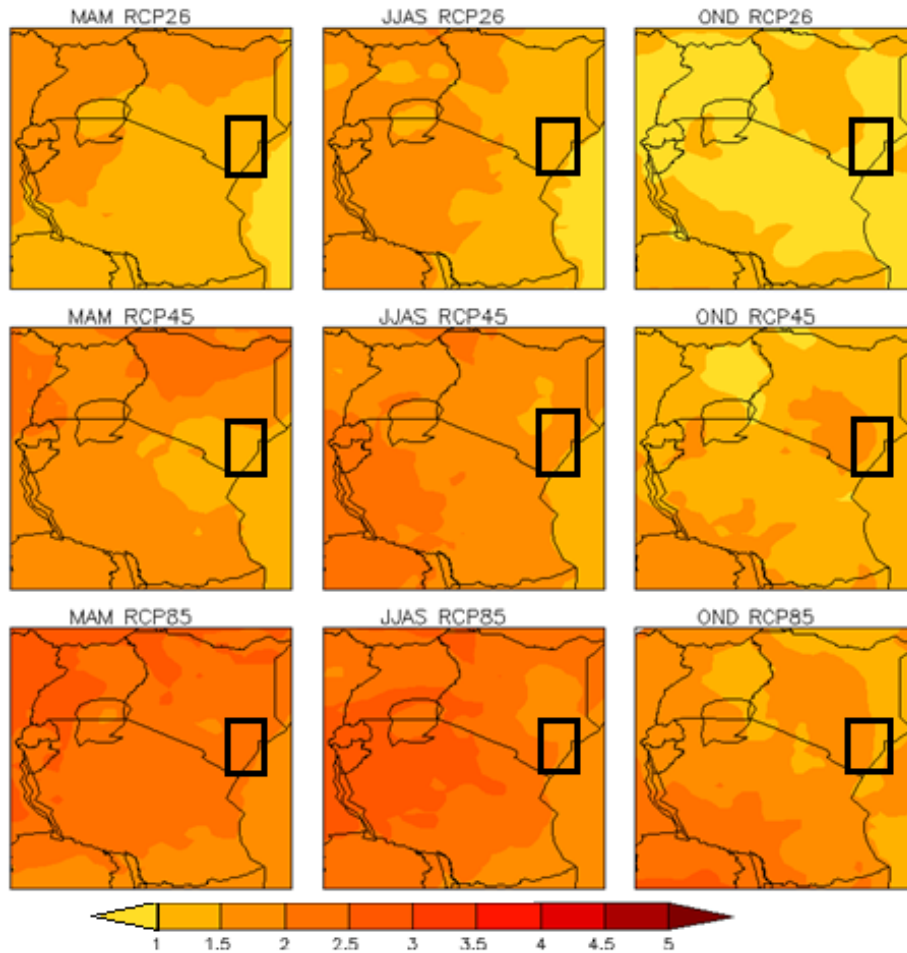


Figure 39: Projected maximum temperature changes over eastern Africa and Tana River County (in box) by 2050s in MAM (1st column), JJAS (2nd column), and OND (3rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1st row), RCP4.5 (2nd row) and RCP8.5 (3rd row) respectively.

By 2050 (Figure 39), maximum temperatures are expected to be 1.0 to 1.5 °C higher under the RCP2.6 and RCP4.5 while under the RCP8.5 scenarios 1.5 to 2.5 °C higher over most parts of the region including the basin studied. In the far future 2070 (Figure 40), projected seasonal maximum temperatures will likely be 0.5 to 1.5 °C higher under the RCP2.6 scenario, which is notably smaller than the changes anticipated by 2050. This is due to the reduction in radiative forcing expected toward the end of the century due to mitigation measures under the RCP 2.6 scenario. In contrast, under the RCP8.5 scenario, the expected annual warming will

likely result in temperatures 1.5 to 3.5 °C higher than the reference period, with far greater warming expected during the relatively dry JJAS season.

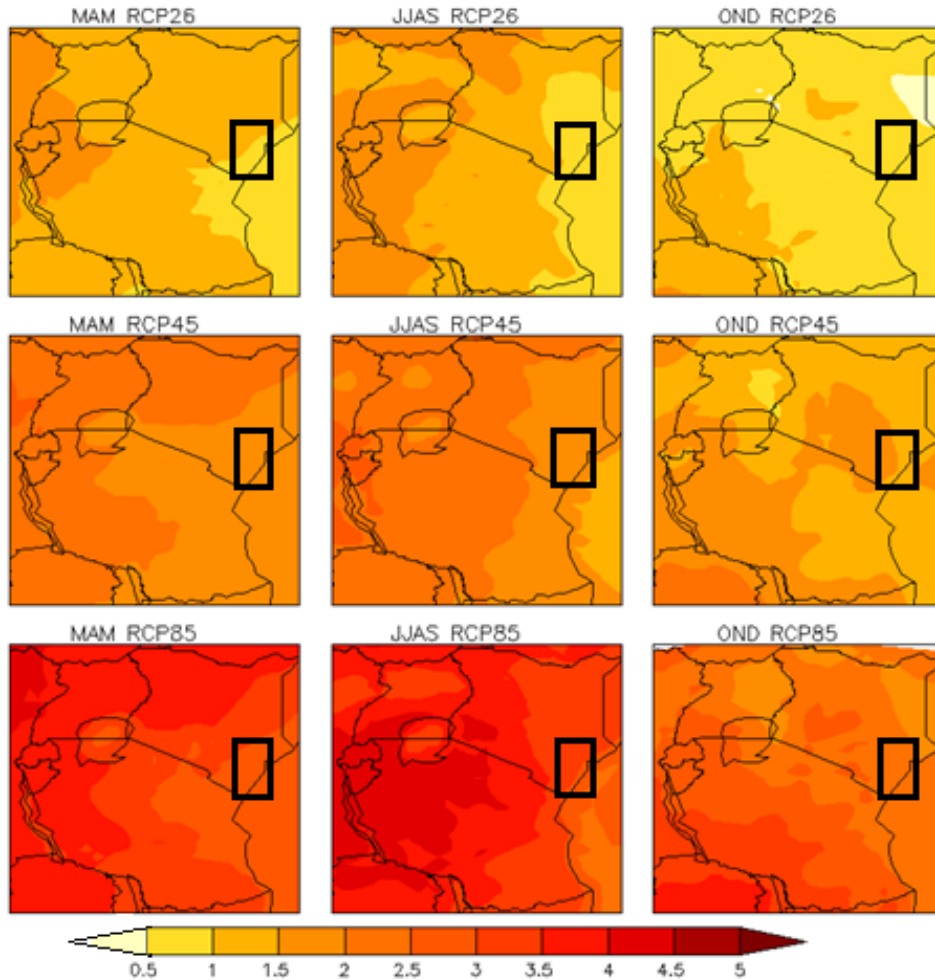


Figure 40: Projected maximum temperature changes over eastern Africa and Tana River County (in box) by 2070s in MAM (1st column), JJAS (2nd column), and OND (3rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1st row), RCP4.5 (2nd row) and RCP8.5 (3rd row) respectively

4.4.3.2 Projected minimum temperature change

The projected spatial changes in the minimum temperatures through time for the three scenarios are shown in Figures 41 to 43. The results suggest that there will likely be a greater increase in the minimum than the maximum temperatures in future. By 2030 (Figure 41), the mean minimum temperatures will likely be 1.0 to 1.5 °C higher under the RCP2.6 and the

RCP4.5 scenarios, but 1.5 to 2.0 °C higher under the RCP8.5 scenario over most parts of the region including the study basin.

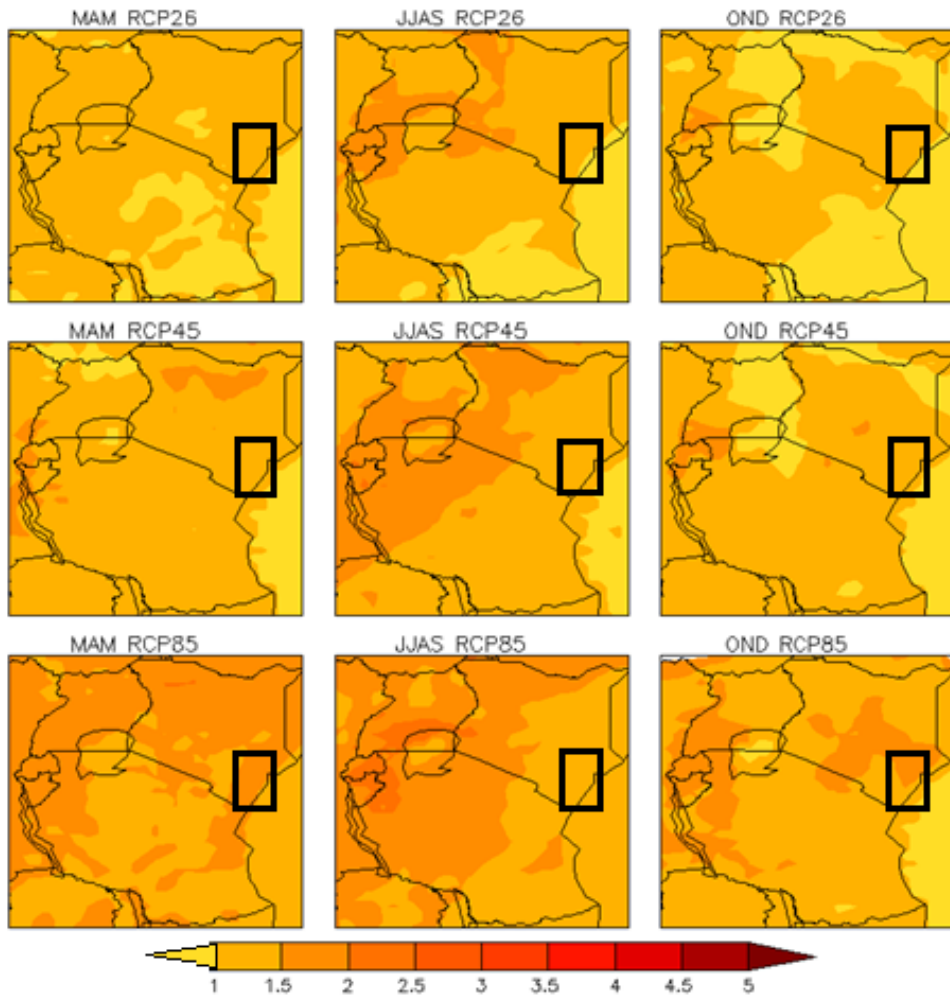


Figure 41: Projected minimum temperature changes over eastern Africa and Tana River County (in box) by 2030s in MAM (1st column), JJAS (2nd column), and OND (3rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1st row), RCP4.5 (2nd row) and RCP8.5 (3rd row) respectively

By 2050 (Figure 42), almost all the region will likely be 1.5 to 2.5 °C warmer than the base period, with the greatest warming expected during the dry season months (JJAS) under the RCP8.5 scenario.

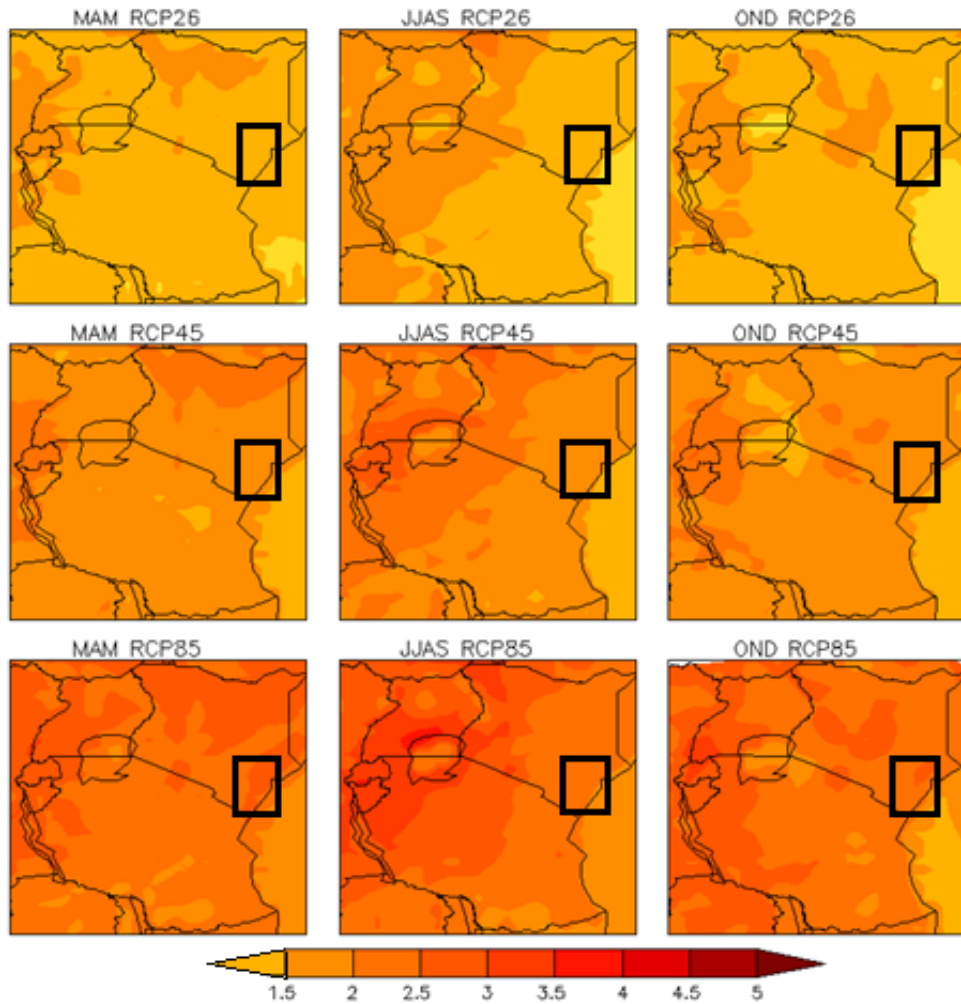


Figure 42: Projected minimum temperature changes over eastern Africa and Tana River County (in box) by 2050s in MAM (1st column), JJAS (2nd column), and OND (3rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1st row), RCP4.5 (2nd row) and RCP8.5 (3rd row) respectively

Similarly, by 2070 (Figure 42), the projected increase in the annual minimum temperatures will likely be 2.5 to 4⁰C higher under the RCP8.5 scenario relative to the base period.

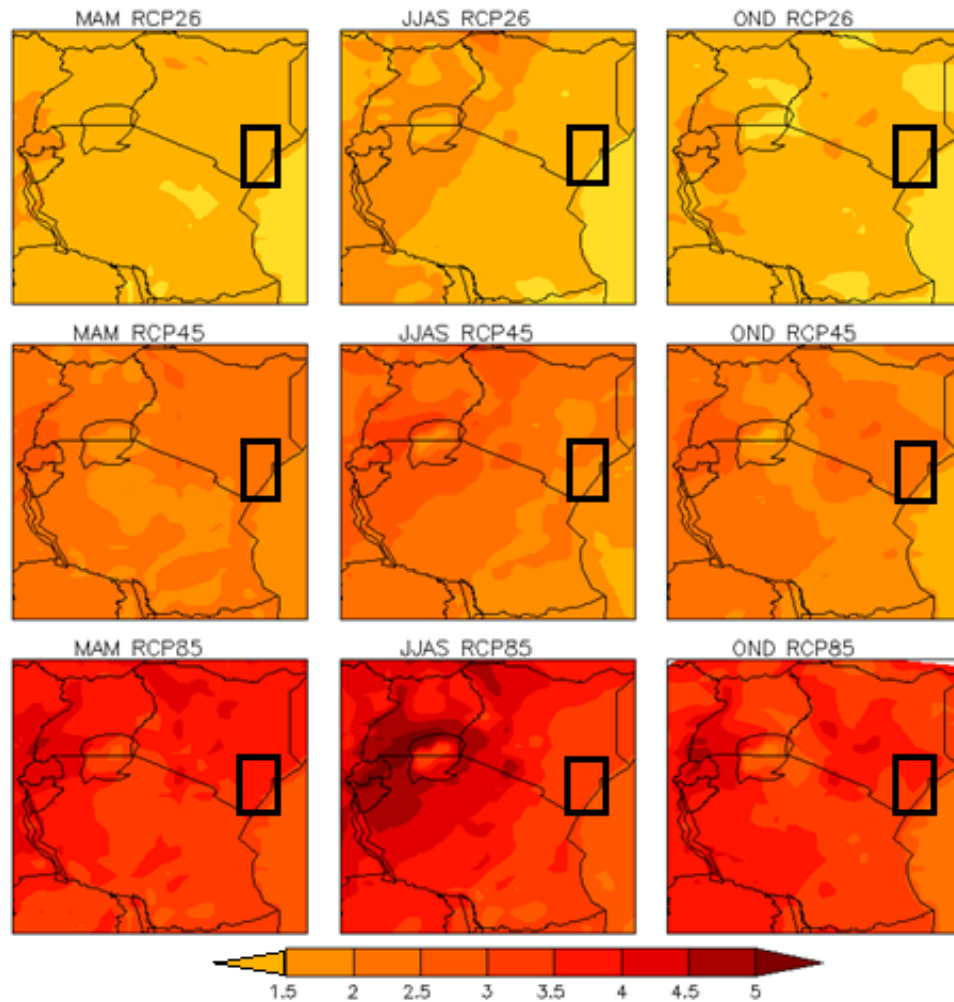


Figure 43: Projected minimum temperature changes over eastern Africa and Tana River County (in box) by 2070s in MAM (1st column), JJAS (2nd column), and OND (3rd column) respectively. Each row corresponds to emission scenarios RCP2.6 (1st row), RCP4.5 (2nd row) and RCP8.5 (3rd row) respectively

The results of projected temporal changes in mean maximum and minimum temperatures under RCP 4.5 and RCP 8.5 scenarios during the two main rainy seasons of MAM and OND is illustrated in Figure 44. The projected changes reveal significant positive trend anomaly over the basin by both the minimum and maximum temperatures.

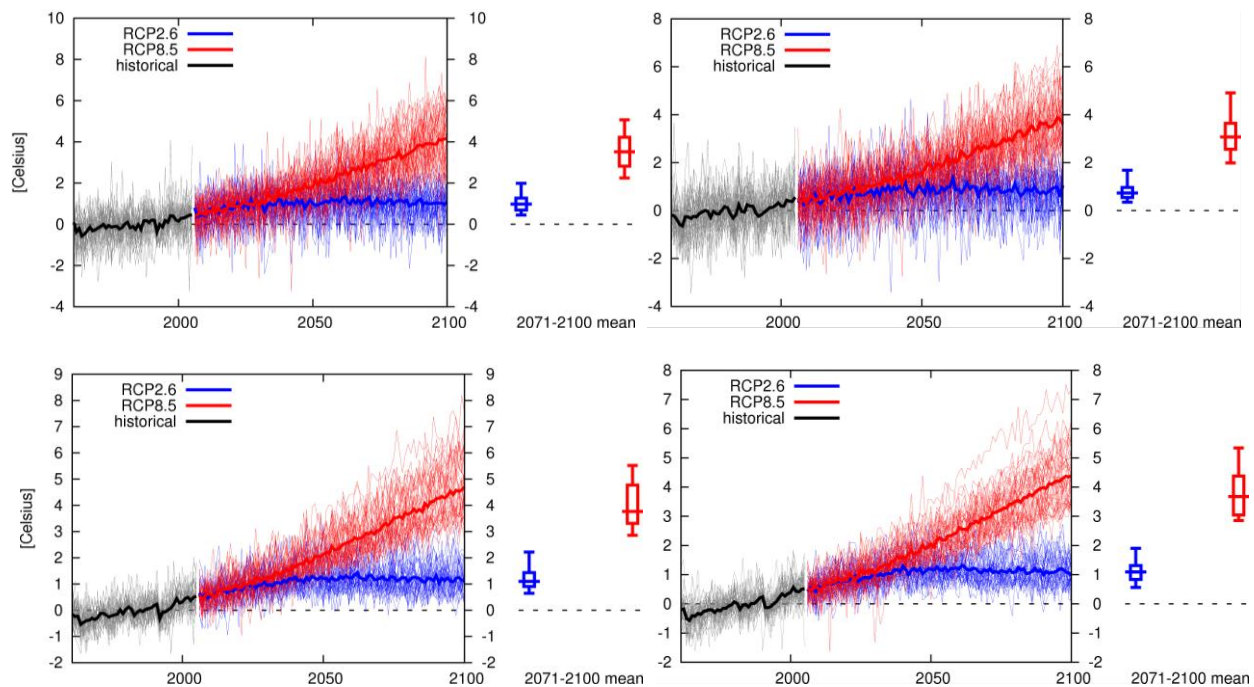


Figure 44: The projected maximum (top row) and minimum (bottom row) temperature change for MAM (left column) and OND (right column) over the lower Tana basin under RCP 2.6 and RCP 8.5 climate scenarios (baseline 1971-2000)

On the left, for each scenario one line per model is shown plus the multi-model mean, on the right percentiles of the whole dataset: the box extends from 25% to 75%, the whiskers from 5% to 95% and the horizontal line denotes the median (50%).

Going by the ensemble means, maximum temperatures are projected to steadily increase uniformly in MAM and OND at a rate of 0.1/0.2 and 0.2/0.3°C/decade respectively under RCP4.5/8.5 scenarios over the basin leading to an approximate temperature increase of 2.5/3.0°C by the middle of the century. On the other hand, minimum temperatures will likely increase at a rate of 0.2/0.3 and 0.3/0.35°C/decade under RCP4.5/8.5 scenarios in both eastern Africa region and Tana River county area leading to an approximate temperature increase of 3/3.5°C by the middle of 21st century. Thus, the entire region will get warmer by the end of 21st century. The

finding indicates that all CORDEX models projects positive future trend in maximum and minimum surface temperature, which is consistent with the findings of the IPCC (2007).

Further, similar results were observed with projections by Schellnhuber *et al* (2013) which indicated a greater certainty and stronger signal of increased mean rainfall with 4⁰C warming as compared to 2⁰C warming. It should however be noted that the projected significant increase in temperature over the eastern Africa region and Tana River County might reverse any meaningful cumulative gains in precipitation expected in the region by the end of 21st Century.

4.4.4 Impacts of the projected climate and implications on agricultural production and related land resources in Tana River County

4.4.4.1 Impacts and implications on crop production

The projected mean rainfall and temperature changes in the lower Tana basin show clear evidence of relatively very little increase in rainfall and significant increase in mean maximum and minimum surface temperature under all the three climate scenarios. It is remarkable to postulate that the net projected rainfall increase in the lower Tana River basin will have no major impacts since the significantly increased temperature would result into moisture lost through evaporation and evapotranspiration. The projected increased temperatures will cause increased crop evapotranspiration leading to depressed crop growth, wilting, decreased yields or crop failure. Most of the crops under these conditions will likely be negatively impacted both during establishment, growth and harvest stages. The projected high increase in mean surface temperature of the region would likely result in reduced area of suitable land for crop production, shortened length of growing seasons and thus potential shrink in major crop yields in the basin. These will adversely affect food security status of the region as well as exacerbate the malnutrition conditions. Thus, the need to mainstream suitable adaptation and mitigation measures in the rainfed agricultural production systems.

Several studies done across the African continent have projected similar negative impacts of the climatic changes to crop production estimated at 3-5% of GDP loss by 2030 timescale (Appendix 11) (Alexander *et al.*, 2011). Thornton *et al.*, (2011) using ensemble of 14 GCMs, projected that the length of crop growing period as a result of rising temperature could be reduced by more than 20% across most of Sub-Saharan Africa countries by 2090s. The impact of increased temperature on crop growth and yield remains critical components in crop

production systems since each crop has optimal temperature levels. Maize crop for example, one of the main staple and widely grown crop in the region (including Tana River County) thrives well between temperature range of 15⁰C and 20⁰C depending on the variety. Maize just like other crops are sensitive to temperature change both during inter- and intra- seasons. This study found that the observed climatology of mean surface temperature across the basin is 30⁰C, which already exceeds the required maize optimal range. By 2030, the projected mean maximum temperature increase of 1.0 °C will pose adverse negative impacts on maize production activities in the season. Lobell *et al.* (2011) found that yields from maize, generally reduce by 1% for each day the crop is subjected to temperatures above its threshold levels.

The increased mean surface temperature in the lower Tana basin will imply that zones presently suitable for maize production such as Kipini, Witu and Mpeketoni and whose production potential lies within its minimum threshold requirement (mean rainfall of 500 mm), will automatically be excluded from maize production, a scenario that will pose serious food insecurity challenges in the entire Tana River County and the wider Northern Kenya corridor that benefits from the basin's production. Thornton *et al* (2011) projected that approximately 5% of the Sub-Saharan Africa region where mixed farming systems are practiced could dramatically undergo a shift to exclusively rangeland because of the increased temperatures, meaning that crop production practices in these regions will no longer be viable. Knox *et al.* (2012) review of publications with crop productivity data in Africa pointed to a mean yield changes of 17% for wheat, 5% for maize, 15% for sorghum, and 10% for millet by 2050.

As a result of the projected climate change and impacts on the production of key staple crops like maize in Witu and Kipini, this study recommends various adaptation measures and strategies that will support such rain-fed productions against the increasing temperature and high rainfall variability within the season. First, there is need for accelerated knowledge generation and capacity building for local farmers, extension officers, County executives or policy makers in the region to help mainstream climate change information and manage the potential climate related risks in the region. Secondly, emphasize on the development of policy, legal and regulatory frameworks that will create an enabling environment for the implementation, promotion and scaling up of identified climate adaptation interventions and risk management solutions. The crop production measures includes but not limited to the use drought tolerant crop varieties, enhanced soil moisture conservation measures and introduction of irrigation

technologies such as drip system to supplement excessive plant water losses, availability and access of downscaled climate information and seasonal forecasts to support management of farm decisions such as type of crop variety, where to grow and potential seasonal risks.

It is noteworthy to note that towards the end of the century, heavier rainfall is projected along the eastern Africa coastline (including south of Tana River County), which could lead to flooding, crop inundation and pest and disease outbreaks. Harvest activities would be impaired, with heightened risk of spoilage. An important adaptation strategy proposed include dealing with increased risk of drought, and increased rainfall variability. Overall, interventions should address the need to conserve soil moisture or add moisture (irrigation), but with sufficient drainage to cope with periodic heavy rainfall. Agronomic practices will need to be put in place to ensure harvesting throughout the year, and diversification of livelihoods with increasing rainfall trend.

4.4.4.2 *Impacts and implications on livestock production*

The projected increase in mean maximum and minimum surface temperature in the lower Tana River basin will exacerbate the current ASAL conditions estimated to cover more than 70% of the region's land surface area. Increasing temperatures would increase evaporation, the severity, length and incidence of drought especially in the pastoral dominated areas such as Garissa, Bura and Garsen. This will imply less water is available for livestock as the pressure on the limited water resources in the region increases. Shrunked water resources alongside increased water demand will shift the water balance in the region, thus causing more challenges to water managers to satisfy demands. The increased water stress will also magnify the already water-related woes and ethnic conflicts.

The projected changes in mean surface temperatures coupled with high rainfall variability will be manifested in changes of livestock feed quality and quantity, feed availability and access, water scarcity, increased livestock disease incidences, heat stress, decline in milk production, increased livestock mortality rates attributed to drought, increased conflicts as a result of the competition for the scarce water points and increased migrations by the pastoralists in search of water and green pasture fields along River Tana and delta. These observations are in agreement with Thornton *et al* (2009) findings that many parts of the African continent will experience greater risk of drought accompanied by livestock losses as a result of the changing climate caused by rise in temperature amongst other factors. In the hinterland areas of Tana River County namely Bura, Garissa and Hola, the optimal stocking density of livestock and especially

the big body animals such as cattle will be reduced. Similarly, by 2030, the maintenance requirements of livestock could be altered in these areas as well as the livestock health through heat stress. Further, the larger savanna ecosystem in the lower Tana basin will be reduced and could result in the reduction extent of savanna grasslands and limited availability of forage for grazing animals. The species composition of the rich Tana River ecosystem could shift and negatively impact the livelihood strategies of communities that depend on them.

Therefore, appropriate adaptation measures must be mainstreamed to minimize adverse projected impacts on livestock, an important source of livelihood amongst pastoral communities in the lower Tana basin. Such measures will include deliberate investment in water pans to store runoff water for use during the prolonged droughts, keeping of more adaptive livestock breeds such as the Borana cattle and camels, investing in livestock related post-harvest technologies such as harvesting and storage of natural grasses during the rainy season, strategies to reduce excessive evaporation through afforestation/re-afforestation programs, de-stocking of livestock to match the land carrying capacity to curb land degradation and finally, timely marketing programs (such as the livestock off-take program) to minimize the economic losses due to livestock losses during the extreme droughts. Livestock feed supplementation during droughts should be enhanced as an adaptation measure. In addition, research should be carried out into improved fodder plant and tree species to increase livestock strength and milk production, which would improve productivity and resilience of both livestock and pastoralists in the event of increased floods and droughts.

4.4.4.3 Impacts and implications on agricultural production and other related land resources in Tana River County

The agricultural production in Tana River County is projected to be adversely affected under all emission scenarios (RCP2.6, 4.5 and 8.5) from the increased mean surface temperature changes, reduced seasonal rainfall and increased rainfall variability. The increased warming in the region will alter the climatic conditions favouring agricultural production. High temperatures will cause increased evaporation and crop evapo-transpiration leading to depressed crop growth, wilting, decreased yields and crop failures. The projected increased mean temperature of 1.0 °C in the region will pose adverse negative impacts on present maize production zones such as Witu

and Kipini. These maize potential zones may likely be turned crop unviable leading to increased food insecurity in the entire Tana River County and other adjacent areas benefitting from the basin's production. Food security of the region will also be affected due to the reduction of land suitable for crop production and the shrinking of yields. Increased warming will likely increase the demand for water from the limited sources especially in the pastoralists dominated zones such as Bura, Garissa and Hola. The scenario is likely to magnify the already existing water-related woes and ethnic conflicts related to other land based resources such as grazing zones and wildlife protected areas such as Tsavo national park.

Therefore, appropriate site specific adaptation measures and programmes need to be implemented to support smallholder farmers and pastoralists from these potential adverse effects. Although the study projects minimal increase in the mean rainfall in the region, the gains from this precipitation will be reversed by the significant increase in the mean surface temperatures, thus resulting to net negative impacts. This study, therefore, recommends various adaptation measures to support communities living in the lower Tana basin against these projected vagaries of climate. These measures include but not limited to the use of drought tolerant crop varieties, soil moisture conservation measures, introduction of water efficient irrigation technologies such as drip system to supplement rainfed production systems, use of downscaled climate information and seasonal forecasts to support farm management decisions, and increased capacity building and sensitization programmes. Similarly, the study recommends that pastoral communities in the lower Tana region mainstreams appropriate adaptation measures with the support from the county government to minimize the adverse projected impacts.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter provides the major conclusions drawn from the study on the basis of the specific objectives and corresponding hypotheses tested. Further, recommendations have been done geared towards policy makers, National and County governments, Kenya Meteorological Services (KMS), farmers and other stakeholders in arid and semi-lands that are directly or indirectly affected by rain-fed agricultural production. Besides the agricultural production sector, the implications of study findings on key land based resources such as water, energy and biodiversity are also highlighted for decision makers to take necessary actions to adapt and mitigate the impacts.

5.2 Conclusions

- There is strong evidence that RCMs provide specific climate information needs that support decision making processes impacting agricultural production and other land based resources.
- Rainfed agricultural production in Tana River County will remain a challenge in future due to low and highly variable seasonal rainfall coupled with increasing mean temperatures. This scenario will adversely affect food security and other livelihood sources in the region. The intensity and frequency of low crop yields, crop failures, water scarcity and land based conflicts are likely to increase in the region.
- The projected warming of 3.0 to 3.5⁰C by mid of 21st century in the lower Tana basin under RCP4.5/8.5 scenarios is likely to enhance seasonal rainfall variability critical for crop and livestock production activities. This implies that appropriate adaptation measures need to be mainstreamed to minimize the adverse effects on crop and livestock productivity.

5.3 Recommendations

The recommendations of this study have been directed to policy makers, National and County governments, Kenya Meteorological Services (KMS), farmers and other stakeholders in ASALs that are directly or indirectly affected by rain-fed agricultural production. Besides focusing on the agricultural production, recommendations also highlights other land based resources such as water, energy and biodiversity management sectors.

5.3.1 Recommendations to policy makers

- ❖ Policy makers planning various developments in ASALs are challenged to mainstream downscaled climate information into development plans. Projected climate information provides valuable insights on the plausible future climatic risks and opportunities that can impact the success of planned short and long-term investments in the region
- ❖ Planning for adaptation and mitigation strategies in a warmer world is no longer an optional approach in ASALs if community livelihoods such as crop and livestock productions in ASALs are to be sustained.
- ❖ Develop appropriate policies that address the potential impacts of extreme climatic events or long-term investment projects in the region such as the Lamu Port Southern Sudan-Ethiopia Transport (LAPSSET) and other Vision 2030 flagship projects which have significant effects to sustainability of ASALs ecosystems and livelihoods

5.3.2 Recommendations to Tana River County government

- ❖ Decision makers and planners need to synchronize climate sensitive land production activities with the projected climatic events (warmer conditions and extremes) to minimize the potential impacts on food security, livelihoods and ecosystem sustainability.
- ❖ Invest in identification of crop varieties with compact growth cycles that are likely to benefit from short term moisture availability in March-May and October to December wet phases.
- ❖ Put emphasis on small bodied and more adapted livestock species with inherent physiological potentials to survive and produce under projected warming trends.
- ❖ Develop robust programs on production and marketing of livestock to minimize possible economic losses associated with extreme climatic shocks (such as drought)

5.3.3 *Recommendations to Kenya Meteorological Services (KMS)*

- ❖ Increase weather/climate observatory points in the region to cover the hinterland areas.
- ❖ Invest more in the maintenance of the existing weather stations.
- ❖ Invest in human resource capacity development and agro meteorological monitoring infrastructure in Tana River County
- ❖ Enhance climate data acquisition, analysis and communication so as to enhance seasonal forecasting, early warning of extreme events and near long-term projections
- ❖ Build the capacity of stakeholders in the region; County government staff, farmers and other service providers on the application of climate information in development planning
- ❖ Enhance the provision of downscaled seasonal weather forecasts (onset, cessation, quantity and distribution) to support the synchronization of agricultural activities such as land preparation, planting, crop selection, seed spacing and other farm management practices that are sensitive to climate

5.3.4 *Recommendations to farmers and pastoralists*

Farmers and pastoralists in Tana River County are highly vulnerable to climatic changes through low yields, crop failures, water-scarcity, limited feeds and increased occurrence of livestock disease. This study recommends the following;

- ❖ Utilize climate change information in planning agricultural activities such type of crops to grow, onset of the rains, appropriate adaptation strategies etc.
- ❖ Adopt water efficient irrigation technologies such as drip systems to supplement rainfed production systems
- ❖ Adopt crop diversification measures to spread agricultural risks frequent in a warming world. The strategies will enhance food security and minimize human suffering.

5.4 Areas for further research

- ❖ Evaluation of the efficacy of CORDEX RCMs in other Counties/regions with different set of observed conditions.
- ❖ Studies of soil-crop –water relations and energy budgets to determine specific crop sensitive phenological stages and consequent effects on crop yields.
- ❖ Studies of impacts of projected warming on land based resources (water supplies, energy, and biodiversity among others).
- ❖ Optimization of government livestock off-take programmes with focus on demystifying the cultural beliefs and taboos relating livestock ownership and population among the pastoral communities.

REFERENCES

- ACIA (2004). Impacts of a Warming Arctic: Arctic Climate Impact Assessment, edited, Cambridge University Press. Cambridge, UK
- Agrawala, S. and Fankhauser, S. (2008). Economic aspects of adaptation to climate change: costs, benefits and policy instruments: executive summary. *Organization for Economic Co-operation and Development (OECD), Paris, France*
- Akinsanola, A. A., Ogunjobi, K. O., Gbode, I. E. and Ajayi, V. O. (2015). Assessing the Capabilities of Three Regional Climate Models over CORDEX Africa in Simulating West African Summer Monsoon Precipitation, *Advances in Meteorology*, vol. 2015, Article ID 935431, 13 pages. doi:10.1155/2015/935431
- Alexander, P., Nabalamba, A. and Mubila, M. (2011). “The Link Between Climate Change, Gender and Development in Africa” in *The African Statistical Journal*, Volume 12: 119-40)
- Alila, P.O. and Atieno, R. (2006). Agricultural Policy in Kenya: Issues and Processes, A paper for the Future Agricultures Consortium workshop, *Institute of Development Studies*, 20-22 March 2006, Available at:
http://www.fao.org/fileadmin/user_upload/fsn/docs/Ag_policy_Kenya.pdf
- Amit Garg, Vimal Mishra and Hem Dholakia (2015). Climate Change and India: Adaptation Gap (2015) - A Preliminary Assessment. *Working paper of Indian Institute of Management Ahmedabad (IIMA) W.P. No. 2015-11-01*
- Anandhi, A. (2009). Role of predictors in downscaling surface temperature to river basin in India for IPCC SRES scenarios using support vector machine, *International Journal of Climatology*, 29(4) 583-603
- Anyah, R.O. and Qiu, W. (2012). Characteristic 20th and 21st century rainfall and temperature patterns and changes over the Greater Horn of Africa. *International Journal of Climatology*, 32, 347–363; DOI: 10.1002/joc.2270
- Anyah, R.O. and Semazzi, F.H.M. (2006). Variability of East African rainfall based on multiyear REGCM3 simulations. *International Journal of Climatology*, 27, 357-371
- Asha latha, K. V., Munisamy G. and Bhat, A. R. S. (2012). Impact of Climate Change on Rainfed Agriculture in India: A Case Study of Dharwad. *International Journal of Environmental Science and Development*, Vol. 3, No. 4, August 2012

- Bader, D.C., Covey, C., Gutowski, W.J., Held, I.M., Kunkel, K.E., Miller, R.L., Tokmakian, R.T. and Zhang, M.H. (2008). [Climate models: An assessment of strengths and limitations](#). *A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*. Department of Energy, Office of Biological and Environmental Research, Washington, D.C
- Beddington, J. (2010). Food security: Contributions from science to a new and greener revolution, *Philosophical Transactions of the Royal Society* 365:61–71
- Beagrie, N. (2010). Keeping Research Data Safe Factsheet: *Charles Beagrie Ltd and JISC*
- Behera, S.K., J.-J. Luo, S. Masson, T. Yamagata, P. Delecluse, S. Gualdi, and A. Navarra, (2003). Impact of the Indian Ocean dipole on the East African short rains: A CGCM study. *CLIVAR Exchanges*, 27, 43–45
- Behera, S.K., J.J Luo, S. Masson, P. Delecluse, S. Gualdi, A. Navarra, and T. Yamagata (2005). Paramount Impact of the Indian Ocean Dipole on the East African Short Rains: A CGCM Study. *Journal of Climate*, 18, 4514-4527
- Benestad, R. E. (2007). An evaluation of statistical models for downscaling precipitation and their ability to capture long-term trends. *International Journal of Climatology*, 27(5) 649-665
- Black, E., Slingo, J.M. and Sperber, K.R. (2003). An observational study of the relationship between excessively strong short rains in coastal East Africa and Indian Ocean SST. *Mon. Weather Rev.*103: 74–94.
- Black, E. (2004). The relationship between Indian Ocean sea-surface temperature and East African rainfall, *Phil. Trans. R. Soc. A* 2005 363, 43-47, DOI: 10.1098/rsta.2004.1474
- Boko, M., I. Niang, A. Nyong, C. Vogel, A. Githeko, M. Medany, B. Osman-Elasha, R. Tabo & P. Yanda. (2007). *Africa in 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*, 433-467.
- Boulard, D., Pohl, B., Cre´tat, J., Vigaud, N. and Pham-Xuan, T. (2012). Downscaling large-scale climate variability using a regional climate model: the case of ENSO over Southern Africa. *Clim Dyn.* DOI 10.1007/s00382-012-1400-6

- Cai, W., Agus, S., Guojian, W., Evan, W., Lixin, W., Karumuri, A., Yukio, M. and Toshio, Y. (2014). Increased frequency of extreme Indian Ocean Dipole events due to Greenhouse Warming. *Nature*, 510, 254-269
- Calzadilla, A., Rehdanz, K. and Toll, R. S. J. (2008). Water scarcity and the impact of improved irrigation management: CGE analysis. Research unit Sustainability and Global Change FNU-160. Hamburg, Germany: *Hamburg University and Centre for Marine and Atmospheric Science, Germany*
- Calzadilla, A., Zhu, T., Rehdanz, K., Tol, R.S. and Ringler, C. (2013). Economy wide impacts of climate change on agriculture in Sub-Saharan Africa. *Ecol. Econ.* 93, 150–165
<http://dx.doi.org/10.1016/j.ecolecon.2013.05.006>
- Capotondi, A., Guilyardi, W. and Kitman, B. (2013). Challenges in understanding and modelling ENSO. *PAGES news* 21, No 2, 58-59
- Carter, T.R., R.N. Jones, X. Lu, S. Bhadwal, C. Conde, L.O. Mearns, B.C. O'Neill, M.D.A. Rounsevell and M.B. Zurek, (2007): New Assessment Methods and the Characterisation of Future Conditions. *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*, 133-171
- Challinor, A.J., Wheeler, T.R., Craufurd, P.Q., Slingo, J.M. and Grimes, D.I.F. (2004). Design and optimization of a large-area process-based model for annual crops. *Agric. Forest Meteorol.*
- Challinor, A.J., Ewert, F., Arnold, S., Simelton, E. and Fraser, E. (2009). Crops and climate change: Progress, trends, and challenges in simulating impacts and informing adaptation. *J Exp Bot* 60(10):2775–2789
- Chambwera, M. and Stage, J. (2010). Climate change adaptation in developing countries: issues and perspectives for economic analysis. *International Institute for Environment and Development (IIED), London, UK*
- Christensen, O. B., Drews, M., and Christensen, J. H. (2006). *The HIRHAM regional climate model version 5, DMI Technical Report 06-17*

- Christensen, J., Hewitson, B.C., Busuioc, A., Chen, A., Gao, X., Jones, R., Kwon, W.T., Laprise, R., Magana, V., Mearns, L., Menenedez, C., Raisaenen, J., Rinke, A., Kolli, R. K. and Sarr, A. (2007). *Regional Climate Projections, in IPCC Fourth Assessment Report "Climate Change 2007: The Scientific Basis", Cambridge University Press*
- Christy, J.R. W.B. Norris, and R.T. McNider. (2009). Surface Temperature Variations in East Africa and Possible Causes. *J. Climate*
- Cline, W. R. (2007). Global warming and agriculture: Impact estimates by country”, *Peterson Institute of International Economics, NW, Washington, D.C., U.S.A. 2007*
- Commission for Africa (2005). Our common interest: Report of the Commission for Africa. London:Commission for Africa.
<http://www.commissionforafrica.org/english/report/introduction.html>.
- Cooper, P. J. M, Rao, K. P. C, Singh, P, Dimes, J, Traore, P. S, Rao, K, Dixit, P. and Twomlow, S. J. (2009). Farming with current and future climate risk: Advancing a ‘Hypothesis of Hope’ for rainfed agriculture in the semi- arid tropics. *Journal of SAT Agricultural Research* 7: 1–19.
- Cooper, P. J. M., Dimes, J., Rao, K. P. C., Shapiro, B., Shiferaw, B. and Twomlow, S. (2008). Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? *Agriculture, Ecosystems and Environment* 126: 24–35
- Cooper, P. J. M., Stern, R. D., M. Noguera and J. M. Gathenya (2013). Climate Change Adaptation Strategies in Sub-Saharan Africa: Foundations for the Future. *INTECH, Earth and Planetary Sciences. 13: 327-356. DOI: 10.5772/55133*
- Daron, J. D. and Stainforth, D.A. (2013). On predicting climate under climate change. *Environmental Research Letters, 8, doi:10.1088/1748-9326/8/3/034021*
- Demeke, A.B., Keil, A. and Zeller, M. (2011). ‘Using panel data to estimate the effect of rainfall shocks on smallholders food security and vulnerability in rural Ethiopia’, *Climate Change, 108: 185–206*
- DFID (2005). Climate Proofing Africa: Climate and Africa’s development challenge. *Department for International Development, London*

- Dinar, A., R. Mendelsonhn, R. Evenson, J., Parikh, A., Sanghi, K., Kumar, J., McKinsey, and S.Longergan (Eds.) (1998). Measuring the Impact of Climate Change on Indian Agriculture, *World Bank Technical Paper 402, Washington, D.C., U.S.A.*
- Dosio, A., Panitz, H. J., Frisius, M. S. and Lüthi, D. (2014). Dynamical downscaling of CMIP5 global circulation models over CORDEX-Africa with COSMO-CLM: evaluation over the present climate and analysis of the added value. *Clim Dyn*, 44:2637–2661. DOI 10.1007/s00382-014-2262-x
- Easterling, W., Aggarwal, P., Batima, P., Brander, K., Erda, L., Howden, M., Kirilenko, A., Morton, J., Soussana, J.F., Schmidhuber, J. and Tubiello, F. (2007). In *Climate Change 2007: Impacts, Adaptation and Vulnerability*, eds Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (Cambridge Univ Press, Cambridge, UK), pp 273–313
- Edstrom, M., Grose, M.R. and Whetton, P.H. (2015). An appraisal of downscaling methods used in climate change research. *Wiley Interdisciplinary Reviews: Climate Change* 6:10.1002/wcc.2015.6.issue-3, 301-319. Online publication date: 1-May-2015
- EEA Technical report (2012): Greenhouse gas emission trends and projections in Europe 2012. *Tracking progress towards Kyoto and 2020 targets. EEA Report. No 6/2012. ISBN 978-92-9213-331-3*
- Endris, H.S., Omondi, P., Jain, S., Lennard, C., Hewitson, B., Chang'a, L., Awange, J.L., Dosio, Patrick Ketiem, A., Nikulin, G., Panitz, H., Büchner, M., Stordal, F, and Tazalika, L. (2013): Assessment of the performance of CORDEX regional climate models in simulating East African rainfall. *Journal of Climate* 26: 8453–8475
- Erenstein, O., Thorpe, W., Singh J. and Varma, A. (2007). Crop-Livestock interactions and Livelihoods in the Trans-Gangetic Plains, India. Crop-livestock interactions scoping study –Report I. *Research Report 10. ILRI (International Livestock Research Institute), Nairobi, Kenya. 89pp*
- FAO (2004). The State of Food Insecurity in the World 2004, Rome
- FAO (2005). Impact of Climate Change, Pests and Diseases on Food Security and Poverty Reduction. *Special Event Background Document for the 31st Session of the Committee on World Food Security, Rome, 23–26 May 2005*

- FAOSTAT (2012) ni secruoser retaw fo esu detargetni no msinahcem elbatpecca yllautuM .
erutlucirgA dna dooF :araknA .hcaorppa oiranecs eht fo noitacilppA .aisA lartneC
.snoitaN detinU eht fo noitazinagrO
- Fowler, H. J., Blenkinsop, S. and Tebaldi, C. (2007). Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. *International Journal of Climatology* 27(12), 1547-1578
- Funk, C.C. and Brown, M.E. (2009). Declining global per capita agricultural production and warming oceans threaten food security. *Food Security*, 1:271–289
- Funk, C., Dettinger, M.D., Michaelsen, J.C., Verdin, J.P, Brown, M.E., Barlow, M. and Hoell, A. (2008). ‘Warming of the Indian Ocean threatens eastern and southern African food security but could be mitigated by agricultural development’, *PNAS – Proceedings of the National Academy of Science*, 105(32): 11081-11086
- Funk, C., G. Senay, A. Asfaw, J. Verdin, J. Rowland, J. Michaelson, G. Eilerts, D. Korecha and R. Choularton. (2005). Recent drought tendencies in Ethiopia and equatorial-subtropical eastern Africa. *Washington DC, FEWS-NET*
- George, A. L. and Bennet, A. (2005). *Case studies and theory development in the social sciences*. Cambridge, MA: The MIT Press.
- Giannini, A., Saravanan, R. and Chang, P. (2003). Oceanic forcing of Sahel rainfall on inter-annual to inter-decadal time scales. *Science*, 302, 1027-1030
- Gillett, N. P., V. K. Arora, G. M. Flato, J. F. Scinocca, and K. von Salzen (2012). Improved constraints on 21st-century warming derived using 160 years of temperature observations, *Geophys. Res. Lett.*, 39, L01704, doi:10.1029/2011GL050226
- Giorgi, F., B. Hewitson, J. Christensen, M. Hulme, H. Von Storch, P. Whetton, R. Jones, L. Mearns, C. Fu (2001): *Regional Climate Information: Evaluation and Projections (Chapter 10)*. In *Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the IPCC* [Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds.)]. *Cambridge U. Press: Cambridge*, pp. 739-768
- Giorgi, F. (2006): Regional climate modeling: status and perspectives. *Journal de Physique*, IV, 139, 101-118

- Giorgi, F., Jones, C. and Asrar, G. R. (2009). Addressing climate information needs at the regional level: the CORDEX framework. *World Meteorological Organization bulletin*, 58, 175-183.
- Glotter, M., Elliott, J., McInerney, D., Best, N., Foster, I., and Moyer, E. J. (2014). Evaluating the utility of dynamical downscaling in agricultural impacts projections. *Proceedings of the National Academy of Sciences of the United States of America*, 111(24), 8776–8781. <http://doi.org/10.1073/pnas.1314787111>
- Girorgil, F., Jones, C. and Asrar, G. R. (2009). Addressing climate information needs at the regional level: the CORDEX framework. *World Meteorological Organization*
- GoK (2010a). National Climate Change Response Strategy, Government Printers, Nairobi.
- GoK (2010b). Agriculture Sector Development Strategy (ASDS)
- Gornall, J., Betts, R., Burke, E., Clark, R., Camp, J., Willett, K. and Wiltshire, A. (2010). Implications of climate change for agricultural productivity in the early twenty-first century. *Philos. Trans. R. Soc. Lond. B Biol. Sci.*, 365: 2973–2989
- Gray, C. and Mueller, V. (2012). ‘Drought and population mobility in rural Ethiopia’, *World Development*, 40 (1): 134–145
- Grell, G., Dudhia, J. and Stauffer, D. (1994). A description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5). NCAR *Technical Note*, NCAR/TN-398+STR
- Hamerlynck, O., Luke, Q., Nyange, T.M., Duvail, S. and Leauthaud, C. (2011). Range extension, imminent threats and conservation options for two endangered primates: The Tana river Red Colobus *Procolobus rufomitratu rufomitratu* (Peters, 1879) and the Tana river Mangabey *Cercocebus galeritu galeritu* (Peters, 1879) in the lower Tana floodplain and delta, Kenya. *African Primates*
- Hastenrath, S., Polzin, D., and Mutai, C. (2007). Diagnosing the 2005 Drought in Equatorial East Africa, *J. Climate*, 20, 4628–4637, doi: 10.1175/jcli4238.1, 2007
- Hellmuth, M.E., Mason, S.J., Vaughan, C., van Aalst, M.K. and Choularton, R. (eds) (2011). A Better Climate for Disaster Risk Management. International Research Institute for Climate and Society (IRI), Columbia University, New York, USA
- Herceg, D., A. Sobel, and L. Sun (2007). Regional modeling of decadal rainfall variability over the Sahel. *Climate Dyn.*, 29, 89–99

- Hewitson, B.C. and Crane, R.G. (1996). Climate downscaling: Techniques and application. *Climate Research*, 7, 85–95
- Hewitson, B.C. and Crane R.G. (2006). Consensus between GCM climate change projections with empirical downscaling: precipitation downscaling over South Africa. *Int J Climatol* 26:1315–1337
- Hewitt, C. D. and Griggs, D.J. (2004). Ensembles-Based Predictions of Climate Changes and Their Impacts (ENSEMBLES). *ENSEMBLES Technical Report No. 1*
- Hove, H., Ecevarria, D. and Parry, J. (2011). *Review of Current and Planned Adaptation Action: East Africa – Somalia*, International Institute for Sustainable Development (IISD), Ottawa, Canada
- ICSU- ISSC (2015): Review of the Sustainable Development Goals: *The Science Perspective*. Paris: International Council for Science (ICSU)
- IFPRI (2009). Climate Change – Impact on Agriculture and Costs of Adaptation”, Food Policy Report International Food Policy Research Institute, Washington, D.C., U.S.A., pp.30
- Indeje, M., Semazzi, F.H.M. and Ogallo, L.J. (2000). ENSO signals in East African rainfall and their prediction potentials. *Int. J. Climatol.* 20: 19–46.
- IPCC (2007): *Summary for Policymakers. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- IPCC (2012): *Glossary of terms*. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 555-564
- IPCC (2014): *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, .C. Genova, B. Girma, E.S. Kissel, A.N. Levy , S. MacCracken, P.R. Mastrandrea, and L.L.

- White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688pp
- IUCN (2003). Tana River, Kenya: integrating downstream values into hydropower planning. *Case studies in wetland valuation no. 6*
- Jenkins, G.S., Gaye, A.T. and Sylla, B. (2005). Late 20th century attribution of drying trends in the Sahel from the Regional Climate Model (RegCM3). *Geophysical Research Letters* 32: doi: 10.1029/2005GL024225. issn: 0094-8276
- Jones, C., Giorgi, F. and Asrar, G. (2011). *The Coordinated Regional Downscaling Experiment: CORDEX an international downscaling link to CMIP5*. CLIVAR Exchanges Newsletter 16:34-40
- Jones, P. G. and Thornton, P.K. (2013). Generating downscaled weather data from a suite of climate models for agricultural modelling applications. *Agricultural Systems* 114, 1-5.
- Jones, C., Robertson, E., Arora, V., Friedlingstein, P., Shevliakova, E., Bopp, L., Brovkin, V., Hajima, T., Kato, E., Kawamiya, M., Liddicoat, S., Lindsay, K., Reick, C. H., Roelandt, C., Segschneider, J. and Tjiputra, J. (2013). 'Twenty – First -Century Compatible CO₂ Emissions and Airborne Fraction Simulated by CMIP5 Earth System Models under Four Representative Concentration Pathways'. *Journal of Climate*, 26 (13):4398-4413
- Kabubo-Mariara, J. and Karanja, F.K. (2007). The economic impact of climate change on Kenyan crop agriculture: a Ricardian approach, *Global and Planetary Change*, Vol. 57 Nos 3/4, pp. 319-330
- Kalra, N., Chander, S., Pathak, H., Aggarwal, P.K., Gupta, N.C., Sehgal, M. and Chakraborty, D. (2007). Impacts of climate change on agriculture. *Outlook on Agriculture* 36, 109–118
- Kamau, J.W., and Mwaura, F. (2013). Climate change adaptation and EIA studies in Kenya. *International Journal of Climate Change Strategies and Management” (IJCCSM)*. 2013;Vol 5(2):152-165
- Katzfey, J., J. McGregor, K. Nguyen and Thatcher, M. (2009). *Dynamical downscaling techniques: Impacts on regional climate change signals*. Proceedings of 18th World IMACS / MODSIM Congress, Cairns, Australia. <http://mssanz.org.au/modsim09>
- Kendon, E., R. Jones, E. Kjellstrom, and J. Murphy (2010), Using and Designing GCM-RCM Ensemble Regional Climate Projections, *Journal of Climate*, 23(24), 6485-6503, doi:10.1175/2010JCLI3502.1.

- Kenya National Bureau of Statistics (KNBS) (2009). *Economic survey 2009*, Government Printer, Nairobi: KNBS
- Ketieme, P.K. Makenzi P.P., Omondi, P., Maranga, K and Wekesa, C. (2013). Trend analysis of climate change and its impacts on crop productivity in the lower Tana River Basin, Kenya. *Octa Journal of Environmental Research*, ISSN: 2321-3655
- Kilembe, C., Thomas, T. S., Waithaka, M., Kyotalimye, M., and Tumbo, S. (2013). Tanzania. In M. Waithaka, G.C. Nelson, T. S. Thomas and M. Kyotalimye (Eds.), *East African Agriculture and Climate Change: A Comprehensive Analysis* (pp. 313-343). IFPRI, Washington, D
- Knox, J., Hess, T., Daccache, A. and Wheeler, T. (2012). Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters*, 7(034032), 8.
- Kurukulasuriya, P., Mendelsohn, R., Hassan, R., Benhin, J., Deressa, T., Diop, M., Eid, H.M., Yerfi Fosu, K, Gbetibouo, G., Jain, S., Mahamadou, A., Mano, R., Kabubo-Mariara, J., El-Marsafawy, S., Molua, E., Ouda, S., Ouedraogo, M., Sene, I., Maddison, D., Seo, N. and Dinar, A. (2006). Will African agriculture survive climate change? *World Bank Economic Review* 20(3):367–388
- Lal, R. (2005). Climate change, soil carbon dynamics, and global food security. In: Lal R, Stewart B, Uphoff N, et al., editors. *Climate change and global food security*. Boca Raton (FL): CRC Press; 2005. p. 113–43
- Lebrun, D., Hamerlynck, O., Duvail, S. and Nyunja, J. (2010). The importance of flexibility: An analysis of the large-scale Tana delta irrigation project in Kenya, implemented under an estate system. In Calas, B. and Mumma Martinon, C.A. (Eds), *Shared waters, shared opportunities*, pp. 261-282. Nairobi: Institut Français de Recherche en Afrique and Hakimani College
- Liwenga, E.T. (2008). Adaptive livelihood strategies for coping with water scarcity in the drylands of central Tanzania. *Physics and Chemistry of the Earth* 33, 775–779
- Lobell, D. B., Bänziger, M., Magorokosho, C. and Vivek, B. (2011). Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change*, 1, 42-45. <http://dx.doi.org/10.1038/nclimate1043>.

- Magombeyi, M.S. and Taigbenu, A.E. (2008). Crop yield risk analysis and mitigation of smallholder farmers at quaternary catchment level: case study of B72A in Olifants river basin, South Africa. *Physics and Chemistry of the Earth* 33, 744–756
- Maingi, J.K. and Marsh, S.F. (2002). Quantifying hydrologic impacts following dam construction along the Tana river, Kenya. *Journal of Arid Environments* 50(1): 53-79.
- Maingi, J.K. and Marsh, S.F. (2006). Composition, structure, and regeneration patterns in a gallery forest along the Tana River near Bura, Kenya. *Forest Ecology and Management* 236: 211–228
- Manji, A. (2012). The 'grabbed state': The legal profession and the 'Ndung'u Report' on illegal/irregular land allocation in Kenya. *Journal of Modern African Studies* 50(3)
- Maraun, D., Wetterhall, F., Ireson, A. M., Chandler, R. E., Kendon, E. J., Widmann, M., Brienen, S., Rust, H. W., Sauter, T., Themeßl, M., Venema, V. K. C., Chun, K. P., Goodess, C. M., Jones, R. G., Onof, C., Vrac, M., and Thiele-Eich, I. (2010): *Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user*, Rev. Geophys., 48, RG3003, doi:10.1029/2009RG000314
- Maurer, E.P. and H.G. Hidalgo (2007). [Utility of daily vs. monthly large-scale climate data: An intercomparison of two statistical downscaling methods](#). *Hydrology and Earth Systems Sciences Discussions* 12: 551-563
- Mburu, B.K., Kung'u, J. B. and Muriuk, J. N. (2014). Effects of Climate Variability and Change on Household Food Sufficiency among Small-Scale Farmers of Yatta District, Kenya. *Journal of Environment, Vol. 03, Issue 02, pp. 19-27*
- McSweeney, C., New, M. and Lizcano, G. (2009). *UNDP climate change country profile: Kenya*. Available online: <http://ncsp.undp.org/sites/default/files/Kenya.oxford.report.pdf>
- Mearns, L., Easterling, W., Hays, C. and Marx, D. (2001). Comparison of agricultural impacts of climate change calculated from high and low resolution climate change scenarios: Part I. The uncertainty due to spatial scale. *Clim Change* 51(2):131–172
- Mearns, L. O., Gutowski, W., and Jones, R. (2009). A regional climate change assessment program for North America,” *Eos*, vol. 90, pp. 311–312
- Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J. and

- Zhao, Z.C. (2007). Global 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
- Mekasha, A., Tesfaye, K. and Duncan, A.J. (2014). 'Trends in daily observed temperature and precipitation extremes over three Ethiopian eco-environments', *International Journal of Climatology*, 34(6): 1990-1999
- Menéndez, C. G., de Castro, Boulanger, M. J.-P. (2010). Downscaling extreme month-long anomalies in southern South America, *Climatic Change*, vol. 98, no. 3, pp. 379–403
- Mireri, C., Onjala, J. and Oguge, N. (2008). *The economic valuation of the proposed Tana Delta Integrated Sugar Project (TISP)*. Nairobi, Kenya: Nature Kenya. Mimeo
- Mishra, V., D. Kumar, A. R. Ganguly, J. Sanjay, M. Mujumdar, R. Krishnan, and R. D. Shah (2014). Reliability of regional and global climate models to simulate precipitation extremes over India, *J. Geophys. Res. Atmospheres*
- Mohino, E., Janicot, S. and Bader, J. (2011). Sahel rainfall and decadal to multi-decadal sea surface temperature variability. *Climate Dynamics*, vol. 37, no. 3, pp. 419–440
- Moinde-Fockler, N.N., Oguge, N.O., Karere, G.M., Otina, D. and Suleman, M.A. (2007). Human and natural impacts on forests along lower Tana River, Kenya: implications towards conservation and management of endemic primate species and their habitat. *Biodiversity and Conservation* 16: 1161-1173
- Moore, N., Alagarwamy, G., Pijanowski, B., Thornton, P., Lofgren, B., Olson, J., Andresen, J., Yanda, P. and Qi, J. (2011). East African food security as influenced by future climate change and land use change at local to regional scales *Climatic Change* DOI 10.1007/s10584-011-0116-7. Published on line June 2011 by Springerlink.com
- Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P. and Wilbanks, T. J. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, 463(7282), 747-756.
- Müller, C., Cramer, W., Hare, W.L., Lotze-Campen, H. (2011). Climate change risks for African agriculture. *Nat. Clim. Change* 108, 4313–4315
<http://dx.doi.org/10.1073/pnas.1015078108>

- Mutai, C. C. and Ward, M. N. (2000). East African rainfall and the tropical circulation/convection on inter-seasonal to inter-annual timescales. *Journal of Climate*, 13, 3915-3939
- Nandozi, C.S., Majaliwa, J.G.M., Omondi, P., Komutunga, E., Aribo, L., Isubikalu, P., Tenywa, M.M. and Makuma H.M. (2012). Regional climate model performance and prediction of seasonal Rainfall and surface temperature of Uganda, *African Crop Science Journal*, Vol. 20, Issue Supplement s2, pp. 213 – 225, Uganda
- New, M., Lister, D., Hulme, M., and Makin, I. (2002). A high-resolution data set of surface climate over global land areas, *Climate Research*, 21(1).
- Nikulin, G., Jones, C., Giorgi, F., Asrar, G., Büchner, M., Cerezo-Mota, R., Christensen, O. B., Déqué, M., Fernandez, J., Hänsler, van Meijgaard, A. E., Samuelsson, P., Sylla, M. B., and Sushama, L. (2012). Precipitation Climatology in an Ensemble of CORDEX-Africa Regional Climate Simulations. *Journal of Climate* 25(18), 6057-6078
- Nyasimi, M, Radeny, M, and Kinyangi, J. (2013). Climate Change Adaptation and Mitigation Initiatives for Agriculture in East Africa, CCAFS Working Paper N. 60, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark. Available online at: www.ccafs.cgiar.org
- Nyingi, D.W., Bart, H., Hamerlynck, O., Gichuki, N., Gathua, J., Ndiwa, T. and Duvail, S. (2011). Species composition and diversity of fishes of the upper and lower Tana River. Communication to the third biennial scientific conference of the National Museums of Kenya
- Ogallo, L. J. (1988). Relationships between seasonal rainfall in East Africa and the southern oscillation. *Int. J. Climatol.* 8, 31–43
- Ogallo, L. J., Jonawiak, J. E. and Halpert, M. S. (1988). Teleconnection between seasonal rainfall over East Africa and global sea-surface temperature anomalies. *J. Meteor. Soc. Japan. Ser. 11*, 66-6. 807-822
- Ojwang, G. O., Agatsiva, J. and Situma, C. (2010). Analysis of climate change and vulnerability risks in the smallholder sector: Case studies of the Laikipia and Narok Districts representing major agro-ecological zones in Kenya. *United Nations, Rome: Department of Resource Surveys and Remote Sensing (DRSRS)*

- Okoola, R.E. (1999a). A diagnostic study of the eastern Africa monsoon circulation during the northern hemisphere spring season. *Int J Climatol* 19:143–168.
- Okoth, G. K. (2011). Potential response of Tea production to climate change in Kericho County. *Diss. University of Nairobi, Kenya,*
- Oludhe, C. (2008). Assessment and Utilization of Wind Power in Kenya – A Review. *Journal of Kenya Meteorological Society Volume 2 (1) 39–52.*
- Omondi, P.A., Ogallo, L.A. and Okoola, R.E. (2009). Decadal Rainfall Variability Modes in observed Rainfall Records over East Africa and their Predictability using Sea Surface Temperature. *Journal of Kenya Meteorological Society 3: 37-54.*
- Omondi, P., Awange, J., Ogallo, L.A., Okoola, R.A., and Forootan, E. (2012a). Decadal rainfall variability modes in observed rainfall records over East Africa and their relations to historical sea surface temperature changes. *Journal of Hydrology, Vol.464-465, Page 140-156, dx.doi.org/10.1016/j.jhydrol.2012.07.003*
- Omondi, P., Laban A. Ogallo, Richard Anyah, J. M. Muthama and J. Ininda (2012b). Linkages between global sea surface temperatures and decadal rainfall variability over Eastern Africa region, *Int. J. Climatol. 33: 2082–2104 (2013), Published online 15 August 2012 in Wiley Online Library: DOI: 10.1002/joc.3578*
- Omondi, P.A., J.L. Awange, E. Forootan, L.A. Ogallo, R. Barakiza, G.B. Girmaw, I. Fesscha, V. Kululetera, C. Kilembe, M.M. Mbatia, M. Kilavi, S.M. King’uyu, P.A. Omeny, A. Njogu, E.M. Badr, T.A. Musa, P. Muchiri, D. Bamanya, and E. Komutunga. (2013a). Changes in Temperature and Precipitation Extremes in the Greater Horn of Africa Region from 1961 to 2010. *International Journal of Climatology 43(4): 1262-1277*
- Omondi, P., Awange, J., Ogallo, L., Ininda, J. and Forootan, E. (2013b). The influence of low frequency sea surface temperature modes on delineated decadal rainfall zones in Eastern Africa region. *Advances in Water Resources, x.doi.org/10.1016/j.advwatres.2013.01.001*
- Omumbo, J., Lyon, B., Waweru, S.M., Connor, S.J. and Thomson, M.C. (2011). Raised temperatures over the Kericho tea estates: revisiting the climate in the East African highlands malaria debate. *Malaria Journal* 2011, 10:12 doi:10.1186/1475-2875-10-12
- Owiti, Z., L.Ogallo and J. Mutemi (2008). Linkages between Indian Ocean Dipole and East African Seasonal Rainfall anomalies. *J. of Meteorological and Related Sciences, ISSN 1995-9834, 2, 1-2, 3-17*

- Paeth, H., Born, K., Podzun, R. and Jacob, D. (2005). Regional dynamical downscaling over West Africa: model evaluation and comparison of wet and dry years. *Meteorology*, 14(3), 349-367
- Parry, M., Canziani, O., Palutikof, J., van der Linden, P., Hanson C, eds (2007). Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge Univ Press, Cambridge, UK)
- Parson, E.A., V.R. Burkett, K. Fisher-Vanden, D.W. Keith, L.O. Mearns, H.M. Pitcher, C.E. Rosenzweig, and M.D. Webster (2007): Global-Change Scenarios: Their Development and Use. In *Sub-report 2.1B of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*. Department of Energy, Office of Biological & Environmental Research
- Platts, P. J., Omeny, P. A. and Marchant, R. (2015). AFRICLIM: high-resolution climate projections for ecological applications in Africa. *African Journal of Ecology* 53:10.1111/aje.2015.53.issue-1, 103-108. Online publication date: 1-Mar-2015
- Popova, Z. and Kercheva, M. (2005). CERES model application for increasing preparedness to climate variability in agricultural planning – risk analysis. *Physics and Chemistry of the Earth* 30, 117–124
- Qian, B., DeJong, R., Huffman, E.C., Wang, H., and Yang, J.Y. (2015). "Projecting yield changes of spring wheat under future climate scenarios on the Canadian Prairies.", *Theoretical and applied climatology*. doi : 10.1007/s00704-015-1378-1
- Republic of Kenya (2005). Economic Survey 2005. Government Printer, Nairobi
- Reddy, V.R. and Pachepsky, Y.A. (2000). Predicting crop yields under climate change conditions from monthly GCM weather projections. *Environ Modell Software* 2000;15:79–86
- Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., and Rafaj, P. (2011). RCP 8.5-A scenario of comparatively high greenhouse gas emissions. *Climatic Change*, 109(1-2), 33-57.
- Rickards, L. and Howden, S.M. (2012). Transformational adaptation: agriculture and climate change. *Crop and Pasture Science*, 2012, 63, 240–250
- Rockel, B., Will, A. and Hense, A. (2008). The regional climate model COSMO-CLM (CCLM). *Meteorol. Z.* 17(4), 347–348

- Rosenzweig, C., J.W. Jones, J.L. Hatfield, A.C. Ruane, K.J. Boote, P. Thorburn, J.M. Antle, G.C. Nelson, C. Porter, S. Janssen, S. Asseng, B. Basso, F. Ewert, D. Wallach, G. Baigorria, and J.M. Winter (2013): The Agricultural Model Inter-comparison and Improvement Project (AgMIP): Protocols and pilot studies. *Agric. Forest Meteorol.*, **170**, 166-182, doi:10.1016/j.agrformet.2012.09.011.
- Roudier, P., Sultan, S., Quirion, P. and Berg, A. (2011). The impact of future climate change on West African crop yields: what does the recent literature say? *Glob. Environ. Change* 21:1073–83
- Ruijs, A., de Bel, M., Kononen, M., Linderhof, V. and Polman, N. (2011). Adapting to Climate Variability: Learning from past experience and the role of institutions, *World Bank Social Development Working Papers no. 124*, World Bank, Washington DC.
- Salami, A., Kamara, A.B. and Brixiora, Z. (2010). Smallholder agriculture in East Africa: Trends, constraints and opportunities. *African Development Bank Group Working Paper Series No. 105*, African Development Bank, Abidjan
- Salath'e, E.P. (2005). Downscaling simulations of future global climate with application to hydrologic modeling. *International Journal of Climatology* 25: 419–436
- Sanchez, P.A., Denning, G.L. and Nziguheba, G. (2009). The African Green Revolution moves forward. *Food Security* 1:37–44
- Santos e Silva, C. M., Silva, A., Oliveira, P. and Lima, K. C. (2013). Dynamical downscaling of the precipitation in Northeast Brazil with a regional climate model during contrasting years. *Atmos. Sci. Let. DOI: 10.1002/asl2.468*
- Schellnhuber, H. J., Hare, W., Serdeczny, O., Schaeffer, M., Adams, S., Baarsch, F. and Rocha, M. (2013). Turn down the heat: *Climate extremes, regional impacts and the case for resilience*
- Schmidli, J., Frei, C. and Vidale, P.L. (2006). Downscaling from GCM precipitation: A benchmark for dynamical and statistical downscaling methods. *International Journal of Climatology* 26: 679–689
- Schreck, C. J. and F.H. M. Semazzi (2004). Variability of the recent climate of eastern Africa. *Int. J. Climatol.* 24, 681–701

- Segele, Z. T., L. M. Leslie, and P. J. Lamb, (2009): Evaluation and adaptation of a regional climate model for the Horn of Africa: Rainfall climatology and interannual variability. *Int. J. Climatol.*, 29, 47–65.
- Seo, N. and R. Mendelsohn (2008). A Ricardian Analysis of the Impact of Climate Change on South American Farms, *Chilean Journal of Agricultural Research*, vol. 68, No. 1, pp.69-79
- Settele, J., R. Scholes, R. Betts, S. Bunn, P. Leadley, D. Nepstad, J.T. Overpeck, and M.A. Taboada (2014): ‘*Terrestrial and inland water systems*’. In Field et al (eds) *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 271-359
- Shongwe, M.E., van Oldenborgh and van Aalst (2009). Projected changes in mean and extreme precipitation in Africa under global warming, *Part II: East Africa. Nairobi, Kenya*, 56 pp.
- Shongwe, M.E., van Oldenborgh, G.J., van den Hurk, B. and van Aalst, M. (2011). Projected changes in mean and extreme precipitation in Africa under global warming Part II: East Africa. *J Clim* 24:3718–3733.
- Sivakumar, M. V. K., Das H. P. and Brunini, O. (2005). Impacts of present and future climate variability and change on agriculture and forestry in the arid and semi-arid tropics. *Clim. Change* 70, 31–72
- Slegers, M.F.W. and Stroosnijder, L. (2008). ‘Beyond the Desertification Narrative: A Framework for Agricultural Drought in Semi-arid East Africa’, *Ambio*, 37(5): 372-380
- Smit, B. and Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. *Global Environmental Change*, 16: 228–292
- Soliman, S. A., Sayedz, M. A., and Jeulands, M. (2009). Impact assessment of future climate change for the Blue Nile basin using a RCM nested in a GCM. *Nile Basin Water Engineering Scientific Magazine*
- Sylla, M. B., Gaye, A. T., Pal, J. S., Jenkins, G. S. and Bi, X. Q. (2009). High-resolution simulations of West African climate using regional climate model (RegCM3) with different lateral boundary conditions, *Theoretical and Applied Climatology*, vol. 98, no. 3-4, pp. 293–314

- Tabor, K. and J.W. Williams (2010). Globally downscaled climate projections for assessing the conservation impacts of climate change. *Ecological Applications*, 20(2): 554-565
- Tadross, M.A., Jack C., and Hewitson, B.C. (2005). On RCM-based projections of change in southern African summer climate. *Geophysical Research Letters*, 32(23), L23713, doi 10.1029/2005GL024460
- Taylor, K.E., R.J. Stouffer and G.E. Meehl (2009). A summary of the CMIP5 experiment design. https://cmip.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf
- Taylor, K.E., Stouffer, R.J. and Meehl, G.A. (2012). An overview of CMIP5 and the experiment design. *Bull Am Meteor Soc* 93(4):485-498, DOI 10.1175/BAMS-D-11-00094.1g
- Tenge, N.G., Mutabazi, A. and Thomas, S.T. (2013). Rwanda', in *East African Agriculture and Climate Change: A Comprehensive Analysis*, Washington, DC: International Food Policy Research Institute
- Terer, T., Ndiritu, G.G. and Gichuki, N. N. (2004). Socio-economic values and traditional strategies of managing wetland resources in lower Tana River, Kenya. *Hydrobiologia* 527(1): 3-14
- Thompson, H.E., Berrang-Ford, L. and Ford, J.D. (2010). Climate Change and Food Security in Sub-Saharan Africa: A Systematic Literature Review, *Sustainability*, 2:2719-2733
- Thornton, P.K., Jones, P.G., Owiyo, T., Kruska, R.L., Herrero, M., Krishtjansson, P., Notenbaert, A., Bekele, N., Omollo, A., with contributions from Orindi, V., Ochieng, A., Otiende, B., Bhadwal, S., Anantram, K., Nair, S., Kumar, V. and Kelkar, U. (2006). *Mapping climate vulnerability and poverty in Africa*. Report to the Department of International Development, ILRI, Nairobi, Kenya. 200pp. Online at <http://www.dfid.gov.uk/research/mapping-climate.pdf>
- Thornton, P., R. Boone, K. Galvin, S. BurnSilver, M. Waithaka, J. Kuyiah, S. Karanja, E. Gonzalez-Estrada and M. Herrero (2007). Coping Strategies in Livestock-dependent Households in East and Southern Africa: A Synthesis of Four Case Studies', *Human Ecology* 35(4): 461-476
- Thornton, P. K., Jones, P. G., Alagarwamy, A. and Andresen, J. (2009). Spatial variation of crop yield responses to climate change in East Africa. *Global Environmental Change*, 19, 54-65. <http://dx.doi.org/10.1016/j.gloenvcha.2008.08.005>

- Thornton, P.K., Jones, P.G., Alagarswamy, G., Andresen, J. and Herrero, M. (2010). Adapting to Climate Change: Agricultural System and Household Impacts in East Africa, *Agricultural Systems*, 103:73-82
- Thornton, P. K., Jones, P. G., Ericksen, P. J. and Challinor, A. J. (2011). Agriculture and food systems in sub-Saharan Africa in a 4°C + world. *Philosophical Transactions of the Royal Society*, 369, 117-136
- UNEP Sourcebook (2008). Integrating Adaptation to Climate Change into UNEP Programming, Nairobi, Kenya
- UNFCCC (United Nations Framework Convention on Climate Change) (2008). *Compendium on methods and tools to evaluate impacts of, and vulnerability and adaptation to climate change*. UNFCCC Secretariat, Bonn. <http://unfccc.int/3922.php>
- UNFCCC (United Nations Framework Convention on Climate Change) (2010). Potential costs and benefits of adaptation options: a review of existing literature. *Technical paper*
- United Nations Economic Commission for Africa (2011). Vulnerability and Climate Change Hotspots in Africa Mapping Based on Existing Knowledge. *Working Paper 2. African Climate Policy Centre, United Nations Economic Commission for Africa*
- UN (2015). Transforming our World: The 2030 Agenda for Sustainable Development. Outcome Document for the United Nations Summit to Adopt the Post-2015 Development Agenda. Available at: <https://sustainabledevelopment.un.org/post2015/transformingourworld>
- Van der Linden, P. and J. Mitchell (Eds.) (2009). ENSEMBLES: Climate change and its impacts. Summary of research and results from the ENSEMBLES project, *Met Office Hadley Centre, Exeter, UK*
- Van Vuuren, D.P., Kok, M.T.J., Girod, B., Lucas, P.L and de Vries B. (2012) Scenarios in global environmental assessments: Key characteristics and lessons for future use. *Global Environ Change* 22(4):884–895.
- Villegas, J. R., and Challinor, A. (2012). Assessing relevant climate data for agricultural applications. *Agricultural and Forest Meteorology* 161, 26-45
- Villegas, J. R., Jarvis, A. and Läderach, P. (2013). Empirical approaches for assessing impacts of climate change on agriculture: The EcoCrop model and a case study with grain sorghum. *Agricultural and Forest Meteorology* 170, 67-78. Online publication date: 1-Mar-2013
- Von Storch, H., H. Langenberg and F. Feser (2000). A spectral nudging technique for dynamical downscaling purposes. *Monthly Weather Review*. 128: 3664-3673

- Wang, L., Ranasinghe, R., Maskey, S., van Gelder, J. M. and Vrijling, J. K. (2015). Comparison of empirical statistical methods for downscaling daily climate projections from CMIP5 GCMs: a case study of the Huai River Basin, China. *International Journal of Climatology*, n/a-n/a. Online publication date: 1-Apr-2015
- Wasike, C.B., Indetie, D., Ojango J.M. K. and Kahi, A.K. (2006). Direct and maternal (co)variance components and genetic parameters for growth and reproductive traits in the Boran cattle in Kenya. *J. Anim. Breed. Genet*
- Weaver, C.P., Lempert, R.J., Brown, C., Hall, J.A., Revell, D and Sarewitz, D. (2013). [Improving the contribution of climate model information to decision making: the value and demands of robust decision frameworks](#). *WIREs Climate Change* 4: 39-60. doi: 10.1002/wcc.202
- Wilby, R. L. and Dawson, C. W. (2013). The Statistical DownScaling Model: insights from one decade of application. *International Journal of Climatology* 33(7), 1707-1719
- Wilby, R. L., and I. Harris (2006). A framework for assessing uncertainties in climate change impacts: Low-flow scenarios for the River Thames, UK. *Water Resource Research* 42, W02419, doi:10.1029/2005WR004065
- Wilby, R., Dawson, C.W. and Barrow, E.M. (2002). SDSM, a decision support tool for the assessment of regional climate change impacts. *Environmental Modelling & Software*. 17. 147–159
- Wilby, R.L. and T.M.L. Wigley (1997). Downscaling general circulation model output: A review of methods and limitations. *Progress in Physical Geography* 21:530-548
- Winkler, J.A., Palutikof, J.P., Andresen, J.A. and Goodess, C.M. (1997). *The simulation of daily temperature series from GCM output. Part II: Sensitivity analysis of an empirical transfer function methodology*. *Journal of Climate* 10, 2514–2532
- World Bank (2007). *World Development Report 2008: Agriculture for Development*. Washington D.C
- World Bank (2010). *Global Strategy to Improve Agricultural and Rural Statistics*. Report number 56719-GLB. Washington, DC: World Bank, United Nations, and Food and Agricultural Organization of the United Nations

- Yang, W., R. Seager, M. A. Cane, and B. Lyon. (2014). The East African long rains in observations and models. *J. Climate*, 27, 7185–7202
- Yin, R. K. (2009). *Doing case study research*. 4th ed. Thousand Oaks, CA: Sage
- Zhang, X.C. (2005): Spatial downscaling of global climate model output for site-specific assessment of crop production and soil erosion. *Agricultural Forest Meteorology*, 135, 215–229
- Zurek, M. and Henrichs, T. (2007). Linking Scenarios across geographical scales in international environmental assessments. *Technological Forecasting and Social Change* 74(8): 1282-1295

APPENDICES

Appendix 1: Summary of merits and limitations of statistical and dynamical downscaling techniques

	Statistical downscaling	Dynamical downscaling
Advantages	<ul style="list-style-type: none"> • Comparatively cheap and computationally efficient • provides point-scale climatic variables from GCM-scale output • can be used to derive not available from RCMs • Easily transferable to other regions such as the Lower Tana • Method based on standard and accepted statistical procedures • the approach is able to directly incorporate observations into method 	<ul style="list-style-type: none"> • The approach produces responses based on physically consistent processes • produces finer resolution information from GCM-scale output that can resolve atmospheric processes on a smaller scale
Disadvantages	<ul style="list-style-type: none"> • The approach requires long and reliable observed historical data series for calibration • the method is dependent upon choice of predictors • Approach is non-stationary in the predictor-predictand relationship • the climate system feedbacks is not included in the approach • Method dependent on GCM boundary forcing; affected by biases in underlying GCM • The downscaling skill is largely affected by domain size, climatic region and season 	<ul style="list-style-type: none"> • The method is computationally intensive • Limited number of scenario ensembles available • Method is strongly dependent on GCM boundary forcing

(Source: Fowler et al., 2007)

Appendix 2: Focused Discussion Group and key interview guide

Introduction

Mr. Ketiem is a PhD student at Egerton University in Njoro Nakuru County conducting research on “*Downscaling climate change information using an ensemble of regional climate models for agricultural production planning: a case study of Tana River County*”. This study aims to downscale regional climate information using CORDEX models to support decision making process for agricultural production and other land related resources. Climate change is one of the greatest threats facing humanity in the 21st Century. Therefore detailed information that helps decision makers synchronizes the agricultural and other development activities with climatic events is very important. Therefore, this focused group discussion is intended to capture your opinions and views on personal experience, historical observation and perception linking the occurrence and intensity of key climate events namely drought and floods. The interview is for research and academic purposes only and I appreciate your contributions. I assure you that your responses will be treated with utmost confidentiality. The responses will be on;

1. What are some of the common extreme climatic events experienced in the region?
Describe the frequency of occurrence and magnitudes.
2. What are some of the impacts observed as a result of these specific events
3. What were the community responses on these extreme events (coping mechanisms)
4. How has the government responded on these events over time?
5. Does the community receive any early warning information with regards to the occurrence of such climatic events
6. What are some of the existing adaptation measures being implemented in the area? And by who and where?
7. In your view, what are some of the strategies required to buffer the communities livelihood systems from vagaries of climate

If you have any further queries about this study, feel free to contact the under mentioned.

Mr. P. K. Ketiem	KALRO Njoro, P.O Private Bag (20107), Njoro. Tel: 0722870608
Dr. P.M. Makenzi	Egerton University, P.O Box 536 (20115), Egerton. Tel: 0724675219
Dr. P.A. Omondi	ICPAC, P.O Box 10304 (00100), Nairobi. Tel: 0720701880
Dr. E.K. Maranga	Egerton University, P.O Box 536 (20115), Egerton. Tel: 0722694378

Appendix 3: List of weather stations in Tana River County

Station Name	Registration block No.	Latitude		Longitude	
Garissa	9039000	0	29S	39	38E
Bura research station	9139003	1	8S	39	54E
Tana irrigation scheme, Galole	9140005	1	31S	40	0E
Garsen station	9240010	2	16S	40	7E
Witu agricultural Office	9240003	2	23S	40	26E
Kipini agricultural Office	9240000	2	38S	40	46E

(Source: Field work)

Appendix 4: The status of climate observation station networks in Kenya

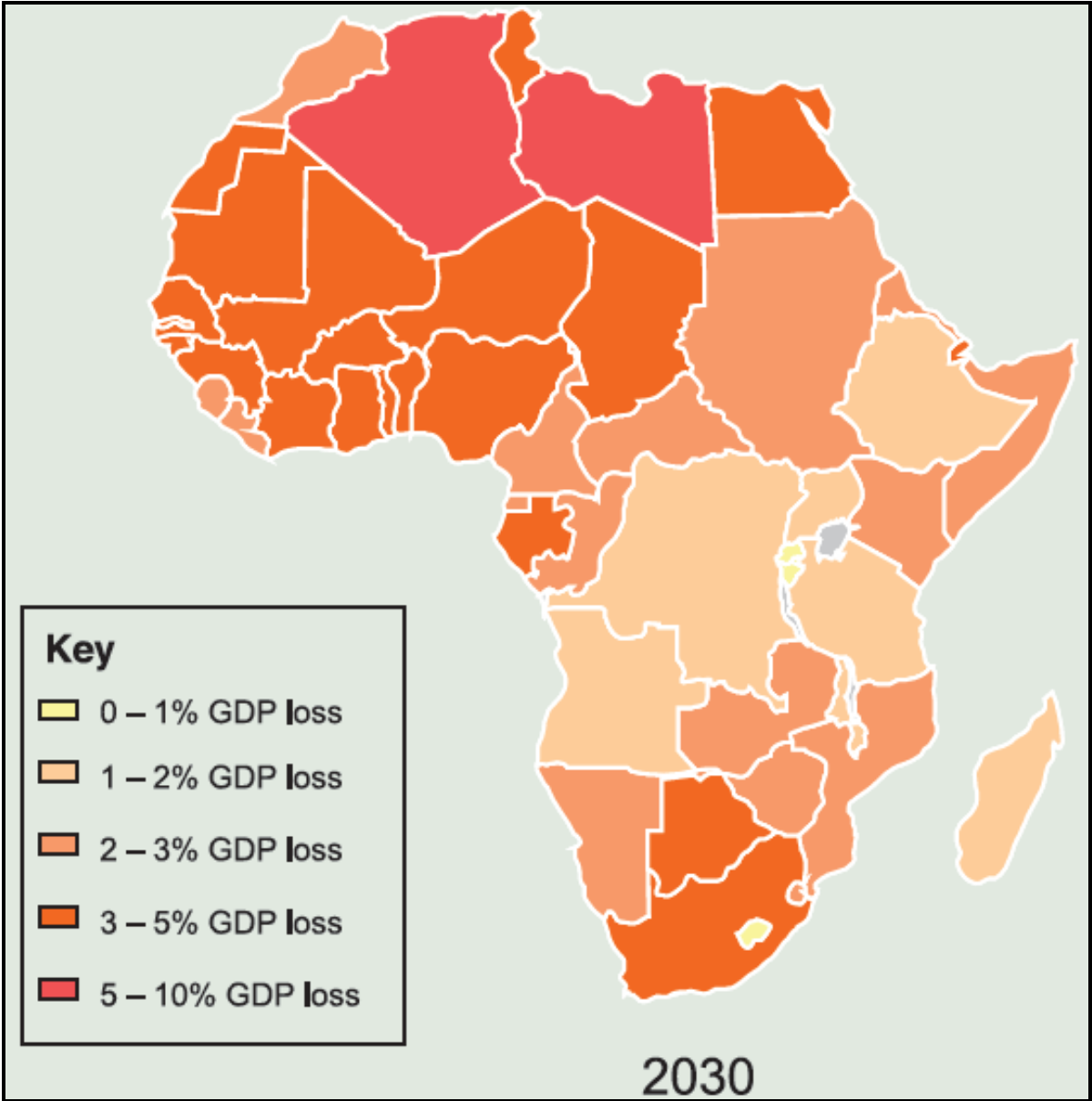
	Present	Operation	Optimum	Required
Surface Station	35	35	70	35
Upper Air Station	3	1	5	2
Agromet	19	16	25	6
Ordinary Climate	200	200	400	200
GAW	1	1	2	1
Marine	2	2	4	2
AWS	13	10	70	57
Rainfall	2000	600	10000	8000
Radars	5	0	5	0

(Source: EAC, 2004)

Appendix 5: Summary of drought and extreme rainfall events and the number of people affected in different parts of Kenya (1971-2010)

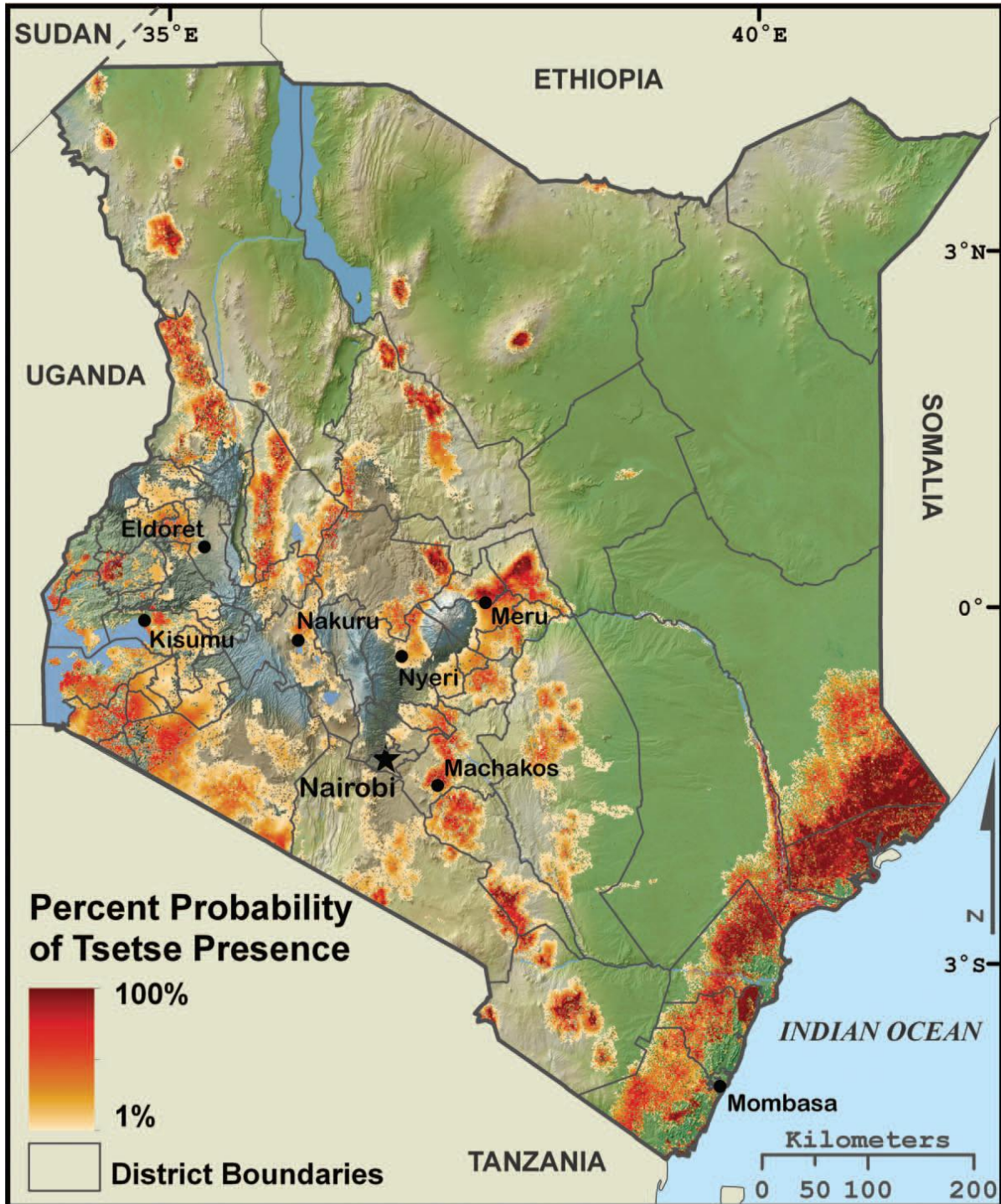
Year	Type of disaster	Area of coverage	People affected
2007/2008	Drought	Widespread	9 million
2007	Floods	Khuvasali, Kakamega	98
2004/2005	Floods	Budalangi, Nyando	34 000
2003	Floods	Budalangi	28 000
2002	Landslides	Meru, Murang'a, Nandi	2 000
1999/2000	Drought	Widespread	4.4 million
1997/98	El Nino	Widespread	1.5 million
1995/96	Drought	ASAL zone	1.41 million
1991/92	Drought	ASAL zone	1.5 million
1985	Floods	Nyando/Western	10 000
1983/84	Drought	Widespread	200 000
1982	Floods	Nyando	4 000
1980	Drought	Widespread	40 000
1977	Drought	Widespread	20000
1975	Drought	Widespread	16 000
1971	Drought	Widespread	150 000

Appendix 6: Annual cost of climate change in Africa in 2030



(Source: Alexander et al., 2011)

Appendix 7: Tsetse ecological distribution (TED) percentage probability map in Kenya



(Source: Messina et al., 2011)

Appendix 8: List of CORDEX RCMs and their details

	CNRM ARPEGE 5.1	DMI HIRHAM5	ICTP RegCM3	CLM com CCLM 4.8	KNMI RACMO2.2b	MPI REMO	SMHI RCA35	UCT PRECIS	UC WRF3.1.1	UQAM CRCM5
Institute	Centre National de Recherches Meteorologiques (CNRM), France	Danmarks Meteorologiske Institut (DMI), Danmark	Abdus Salam International Centre for Theoretical Physics (ICTP), Italy	Climate Limited-Area Modelling (CLM) Community (www.clim-community.eu)	Koninklijk Nederlands Meteorologisch Instituut (KNMI), Netherlands	Max Planck Institute (MPI), Germany	Sveriges Meteorologiska och Hydrologiska Institut (SMHI), Sweden	University of Cape Town (UCT), South Africa	Universidad de Cantabria, Spain	Universit_e du Qu_ebec_a Montr_eal (UQAM), Canada
Short name	ARPEGE	HIRHAM	RegCM3	CCLM	RACMO	REMO	RCA	PRECIS	WRF	CRCM
Projection resolution	Polar, stretching factor 2 (t179)	Rotated pole 0.44 ⁰	Mercator 50km	Rotated pole 0.44 ⁰	Rotated pole 0.44 ⁰	Rotated pole 0.44 ⁰	Rotated pole 0.44 ⁰	Rotated pole 0.44 ⁰	Mercator 50km	Rotated pole 0.44 ⁰
Vertical coordinate/levels	Hybrid/31	Hybrid/31	Sigma/18	Terrain following/35	Hybrid/40	Hybrid/27	Hybrid/40	Hybrid/19	Terrain following ETA/28	Hybrid/56
Advection	Semi-Lagrangian	Semi-Lagrangian	Eulerian	Fifth-order upwind; Baldauf (2008)	Semi-Lagrangian	Semi-Lagrangian	Semi-Lagrangian	Eulerian	Eulerian	Semi-Lagrangian
Time step (sec)	1200	600	100	240	720	240	1200	300	240	1200
Convective scheme	Bougeault (1985)	Tiedtke (1989)	Grell (1993); Fritsch and Chappell (1980)	Tiedtke (1989)	Tiedtke (1989)	Tiedtke (1989)	Kain and Fritsch (1990, 1993)	Gregory and Rowntree (1990); Gregory and Allen (1991)	Kain (2004)	Kain and Fritsch (1990); Kuo (1965)
Radiation scheme	Morcrette (1990)	Fouquart and Bonnel (1980); Mlawer et al.(1997)	Kiehl et al. (1996)	Ritter and Geleyn (1992)	Fouquart and Bonnel (1980)	Morcrette et al. (1986); Giorgetta and Wild (1995)	Savijärvi (1990); Sass et al. (1994)	Edwards and Slingo (1996)	Dudhia (1989); Mlawer et al. (1997)	Li and Barker (2005)
Turbulence vertical diffusion	Mellor and Yamada (1982)	Louis (1979)	Holtstlag et al. (1990)	Herzog et al. (2002); Buzzi et al. (2011)	Eddy-diffusivity (first-order K) mass flux approach	Louis (1979)	Cuxart et al. (2000)	Wilson (1992)	Hong et al. (2006)	Benoit et al. (1989); Delage (1997)
Cloud microphysics scheme	Ricard and Royer (1993)	Tiedtke (1989); Tompkins (2002)	Subgrid explicit moisture scheme (SUBEX); Pal et al. (2000)	Doms et al. (2007); Baldauf and Schulz (2004)	Tiedtke (1993)	Lohmann and Roeckner (1996)	Rasch and Kristjánsson (1998)	Smith (1990)	WRF single-moment 5-class microphysics scheme (WSM5); Hong et al. (2004)	CLASS 3.5; Versegny (2000)
Land surface scheme	ISBA; Douville et al. (2000)	Schulz et al. (1998); Hagemann (2002)	BATS1E; Dickinson et al. (1993)	TERRA-ML; Doms et al. (2007)	TESSEL; ECMWF (2006)	Hagemann (2002) Rechid et al. (2009)	Samuelsson et al. (2006)	MOSES2; Essery et al. (2003)	Smirnova et al. (2000)	CLASS 3.5; Versegny (2000)
Latest reference and comments	Déqué (2010)	Christensen et al. (2006)	Pal et al. (2007)	Rockel et al. (2008); Baldauf et al. (2011)	van Meijgaard et al. (2008); based on ECMWF cycle 31r1; ECMWF (2006)	Jacob (2001) Jacob et al. (2007)	Samuelsson et al. (2011)	Jones et al. (2004)	Skamarock et al. (2008)	Zadra et al. (2008)

(Source: Nikulin et al., 2012)

