FUTURE RAINFALL PROJECTIONS FOR RWANDA USING STATISTICAL DOWNSCALING

NTIKUBITUBUGINGO Etienne
College of Science and Technology

School of science

Master of science in atmospheric and climate science

2018

FUTURE RAINFALL PROJECTIONS FOR RWANDA USING STATISTICAL DOWNSCALING

By

NTIKUBITUBUGINGO Etienne
Reg.No: 217290949

A dissertation submitted in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE IN ATMOSPHERIC AND CLIMATE SCIENCE

In the College of Science and Technology

Supervisor: Professor SAFARI Bonfils

Co-Supervisor: MUTABAZI Alphonse

October, 2018

Declaration

I declare that this work is the result of my own toiling and has never been submitted anywhere for any award.

Etienne NTIKUBITUBUGINGO

Signed……………………………………………..

Date………………………………………………..

ACKNOWLEDGEMENT

This work is the fruit of the efforts of many people to whom I feel greatly indebted.
A sincere acknowledgment is addressed to Professor Bonfils SAFARI and Mr Alphonse MUTABAZI who kindly accepted to supervise this work and to generously provide data, manuals and other facilities in addition to their valuable guidance.

My gratitude also goes to my classmates for their great sense of humanity and understanding, availability and disposition to assist where necessary. Their moral and intellectual support was of great help for me.

Last but not least, I am very grateful to all lecturers who shared knowledge with us during this research program. Without them, this work could have not started. Their great paternal sense and understanding, allowed me to become who I am today. May you feel rewarded by this humble acknowledgement!

ABSTRACT

Rainfall variability over Rwanda is of major concern as the people's welfare always relies on water availability, food security, environmental sustainability, etc. Policy makers need a complete information on rainfall to plan accordingly.

The objective of this research was to project future rainfalls over Rwanda using statistical downscaling method. To achieve this, data from Meteo Rwanda (station data) and CORDEX output historical data were used. Different models were evaluated and one of them showed a better performance compared to others. Graph and statistical methods were used in the process of model validation. The RMSE, MBE, Index of agreement and correlation coefficient are the statistical measures used. Model performance was checked on monthly and seasonal basis while projections were done on annual, seasonal, decadal and climatological basis. CLMcom RCM driven by CNRM-CM5, showed a better performance than other models and was used in projections.

As the rainfall distribution over Rwanda follows a topographical pattern, climate zones over Rwanda have been defined and stations were selected so as to cover all the climate zones. Future rainfall projections focused mainly on MAM and OND as they are the two rainy seasons experienced by East African region countries including Rwanda.

The findings of this research demonstrated the distribution and variability of rainfall where high amount rains at the western part of the country and reduces when moving to the east. In general, projections showed increasing rainfall patterns under all scenarios at five of the selected seven stations. The decreasing patterns were projected at Gicumbi and Nyamagabe stations. For the seasonal rains, there are fluctuations from a decrease to the increase and vice versa. A significant decrease was projected at Gicumbi during short and long rain seasons while Kamembe, Nyamagabe and Ngoma showed a decrease during MAM. Rubavu station is likely to experience extreme rainfall which may cause disasters like floods and landslides while Gicumbi is likely to experience droughts.

LIST OF ACRONYMS

CHIRPS: The Climate Hazard Group Infrared Precipitation with Stations
CORDEX: Coordinated Regional Climate Downscaling Experiment
ENSO: El Niño Southern Oscillation

IOD: Indian Ocean Dipole

DMI: Dipole mode index

EEA: Equatorial Eastern Africa

ENACTS: Enhancing National Climate Services

RCMs: Regional Climate Models

GCMs: Global Climate Models

NAPA: National Action Programs for Adaptation to Climate Change

GDP: Gross Domestic Product

MINAGRI: Ministry of Agriculture

RAB: Rwanda Agriculture Board

ASL: Above Sea Level

SST: Sea Surface Temperature

IPCC: Inter-Governmental Panel on Climate Change

IRI: International Research Institute for Climate and Society

ITCZ: Inter-Tropical Convergence Zone

MAM: March –April-May

OND: October-November-December

JJAS: June-July-August-September

JJA: June-July-August

WRCP: World Climate Research Program

CMIP5: WCRP Coupled Model Intercomparison Project Phase 5

MINITERE: Ministry of Lands, environment, forestry, water and mine

MJO: Madden-Julian Oscillation

mm: millimeter

NE: North East

SE: South East

QBO: Quasi-Biennial Oscillation

RCPs: Representative Concentration Pathways
SH: Southern Hemisphere

SON: September to November

MAE: Mean Absolute Error

MBE: Mean Bias Error

MIDIMAR: Ministry of Disaster Management and Refugee Affairs

RMSE: Root Mean Square Error

Table of Contents

Table of Contents

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: GENERAL INTRODUCTION

1.1 Background

Rwanda is a small, landlocked country in Equatorial East Africa, covering an area of 26 338 km^2. It is located within latitudes 1° -3° South and longitudes 28°-31°East. It is surrounded by Uganda in the North, Tanzania in the East, Burundi in the South and Democratic Republic of the Congo in the West. It has a complex topography which includes mountains, valleys and hills.

The main economic activities like agriculture rely on rainfall. Recent studies showed variability in spatial and temporal distribution of rainfall in Rwanda for the last two decades. Rainfall is an important parameter of weather and climate which affects the economy of a country.
The climate of Rwanda is humid and modified by rain forests and Savannah. The central and eastern parts of the country are generally of semi-arid type owing to their position in the rainy shadow of the western highlands.

1.2 Problem Statement

In the 21st century, climate change is one of the greatest environmental threats to the world, and the changes in climate extremes are having greater negative impacts on humans and the natural environment than the changes in mean climate[1].

Precipitation extremes are of primary concern as these events are responsible for large part of climate related problems. Natural systems are also affected by changes in precipitations extremes causing shifts in ecosystem distributions, extinctions and altering morphology of behavior[2][3]

In the East African countries, rainfall is the climatic factor of maximum significance with extreme occurrences resulting in frequent droughts and floods, which are often associated with food, energy and water shortages, loss of life and property, and many other socio-economic challenges [4]. Agriculture, being the main economic activity in the region, is highly vulnerable to the amounts and distribution of rainfalls. Rainfall variability that occurred in Rwanda has caused problems, like infrastructure, soil, crop damage and death of people mainly in western parts of the country, where the average rainfall is high [5].

Future changes in climate will be felt not only through changes in mean precipitation, but also through altered seasonality, which in turn influences the growing season and crop yields, the length of the malaria transmission season, the supply of hydroelectric power and surface water supplies.

Currently, there is a gap in understanding of the physical and dynamical processes contributing to the interannual variability and the observed changes in precipitation. There is gap also in researches related to future rainfall projections[4].

Different studies have been done on rainfall variability over Rwanda and east African region but there are no works done on rainfall projection especially for Rwanda. Therefore, this study seeks to project rainfall over Rwanda using statistical downscaling.

1.3 Objectives

The main objective of this research was to project rainfall over Rwanda using statistical downscaling. To achieve this, other specific objectives have been set such as

- The determination of spatial-temporal variability of rainfall over Rwanda.
- Assessment of the performance of CORDEX RCMs in simulating the climate of Rwanda
- To determine the projected changes in rainfall over Rwanda.

This study provided information on future rainfall trends over Rwanda in order to be aware of droughts resulting from rainfall scarcity and floods resulting from heavy rains.

It also contributed to filling the gap of such studies in Rwanda as no enough studies on rainfall projections over Rwanda were available.

1.4 Hypothesis of the Study

Rainfall over Rwanda undergone strong variability, resulting in properties damage. There has been an increase in frequency of rainfall extremes and variability of rainfall seasons. That variability is likely to continue even in the future.

1.5 Justification of the study

The main economic activity in Rwanda is agriculture, contributing about 80% of GDP. Rainfall extremes affect crop production resulting in food insecurity, infrastructures are damaged and even there is loss of lives.

Clearly, understanding the pattern and quantity of rainfall over Rwanda is of vital importance for policy makers, disaster managers and climate risk management activities in the country.

1.6 Study area

Rwanda experiences two rain seasons, MAM and OND and two dry seasons, JF and JJAS annually. Rainfall over Rwanda is locally influenced by topography and its distribution follows the change in altitude. Apart from the influence of topography, the climate of Rwanda is also moderated by the presence of a large number of water bodies, like Lake Kivu which covers most of the length of Rwanda's western border.

Other important lakes include Burera and Ruhondo in the north, Muhazi, Rweru, Ihema etc in the east. The main rivers are Nyabarongo and Akanyaru which mix to form Akagera.

During this research, rainfall data were collected from different meteorology stations over the country. Figures 1 and 2 show respectively different climatic zones of Rwanda and meteorology stations from which data have been drawn.

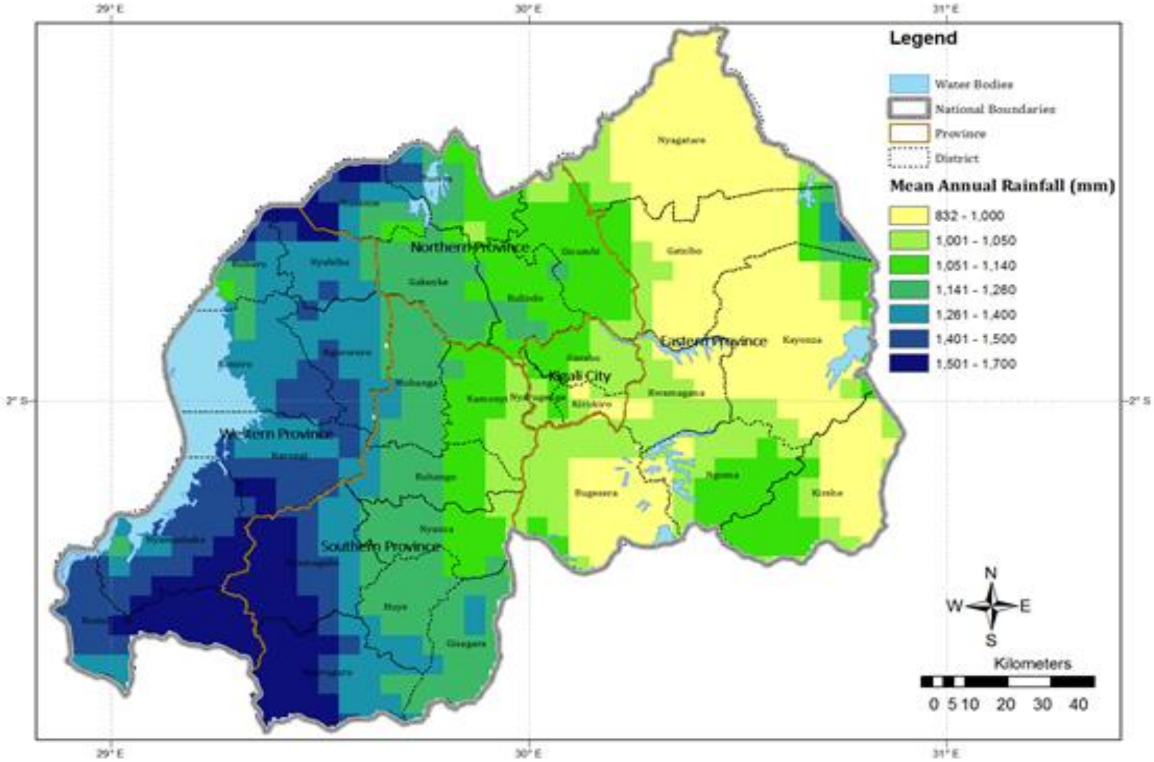

Figure 1: Rainfall zones of Rwanda

Source: *http://www.meteorwanda.gov.rw/index.php?id=30&*

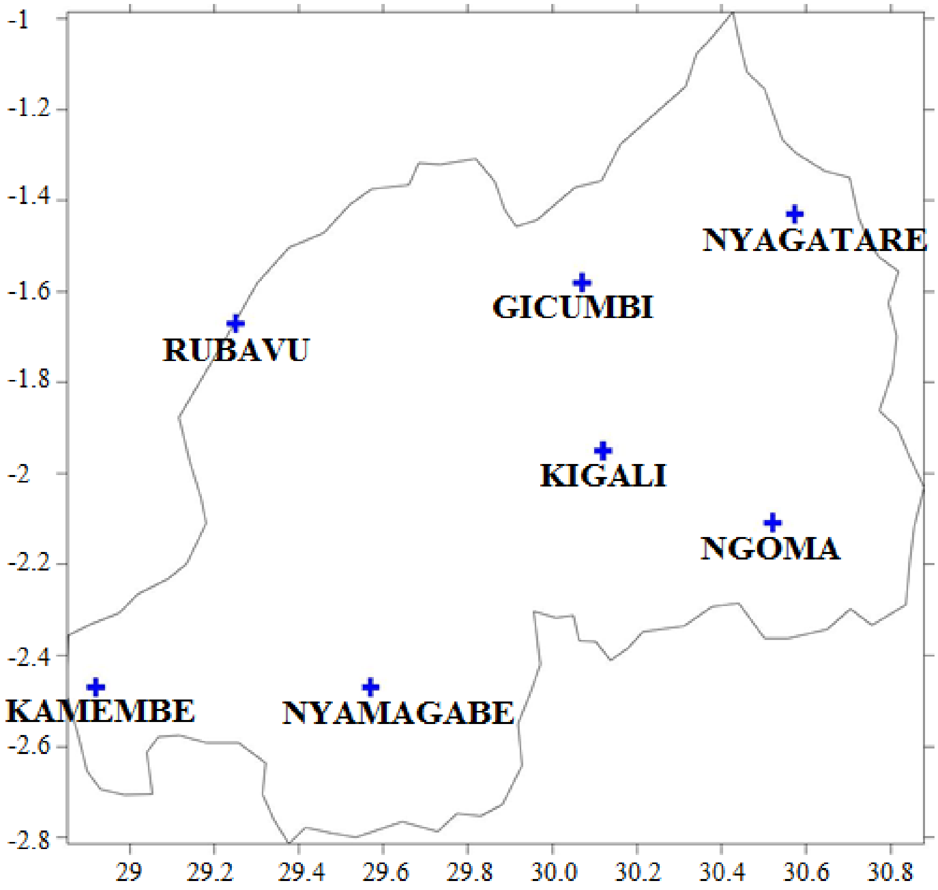

Figure 2: Selected Meteorological stations

Source [6]

CHAPTER 2: LITTERATURE REVIEW

2.1 Precipitation climatology of Rwanda

The climate of Rwanda is cooler and wetter in the west, mainly because of the high mountains, and warmer and drier in the east, where the elevation is lower**.** The variable altitude (950 to 4,500m ASL) influences that climate and leads to considerable differences in rainfall across the country.
In general, the rainfall over Rwanda increases westward. High rainfall amount in the western region is a result of westerly winds which bring moisture from the Congo basin. Western highlands also enhance convective rainfall development through orographic lifting. The low rainfall amounts over the eastern part may be due to the easterly wind which injects moisture from Lake Victoria and Indian Ocean and to the lack of orographic lifting [6].

Rainfall is irregular and sometimes causes periods of drought. Based on topography, there are four distinct climatic regions; the eastern lowlands, the central plateau, the Congo-Nile ridge and volcanic chains of Birunga with increasing altitude and rainfall amounts respectively [7].

The mean annual rainfall is 1,028mm/year but, in the lowlands (East and Southeast), rainfall is less abundant with around 700-970 mm/year[8]. There are two rainy seasons, the ‘long’ rains from March to May and the ‘short’ rains from October to December[9].

In recent two decades, droughts and floods frequency increased and there are indications that this variability may increase even in the future, raising the potential risks of landslides, floods and soil erosion. Flooding and landslides are frequent in the western areas while droughts occurred in East and Southeast of the country. Major flood events that occurred in 1997, 2006, 2007, 2008, and 2009 have caused problems, like infrastructure and crop damage. Thus, the knowledge of future rainfall trends will help policy makers to plan accordingly.

2.2 Regional climatic variability of rainfall

Rwanda, as other East African countries experiences a bimodal pattern of rainfall, which is driven primarily by the progression of the Inter-Tropical Convergence Zone (ITCZ).

East African region has the most varied topography including large lakes, rift valleys and snow-capped mountains around the equator. This heterogeneity gives rise to dramatic variations in climatological mean rainfall totals[10][11].

In addition, seasonal rainfall anomalies can tend to have a coherence that is confined across small sub regions.

In East Africa and tropical region as a whole, variability of rainfall results from complex interactions of forced and free atmospheric variations including the interactions between sea surface temperature (SST) forcing, large-scale atmospheric patterns and synoptic scale weather disturbances including the Intertropical Convergence Zone(ITCZ), monsoonal wind systems and trade winds, El-Nino/Southern Oscillation(ENSO) events, persistent mesoscale circulations, tropical cyclones, subtropical anticyclones, Jet streams, easterly/westerly wave perturbations and extratropical weather systems [4][12][13][14].

For Rwanda, on the above adds other factors like the Congo air mass, Inter-seasonal wave variation, regional and local topography, lake Victoria air mass, large water bodies (e.g. Lake Kivu), and large forests[15][16].

Studies like Schreck and Semazzi (2004) showed that during the 20th century, the region of East Africa experienced an intensifying fluctuation of rainfall patterns on the decadal timescale. This was characterised by increasing rainfall over the northern sector and declining amounts over the southern sector.

The frequency of these fluctuations in excessive and deficit of rainfall has increased from less than 3 events per year in 1980s to 10 events per year from 2000 to 2006 with particular increase in floods[17].The main drivers of regional rainfall are discussed in the next sections.

2.2.1 Intertropical Convergence Zone

This is a point where the dry northern easterly and wet southern easterly winds meet. It is characterised by low pressures, the maximum humidity and the convergence of winds[18].

The ITCZ migrates from southern to northern Tropics and back crossing Rwanda twice a year; this leads to the onset of two rainy seasons; the ‘long rains occur as it moves north and the ‘short rains on its return to South.

The rainfall distribution achieves maxima during the two transition seasons but this may be modulated from season to season by the interactions between the ITCZ and changes in the local circulation systems caused by land surface heterogeneity or by variable vegetation characteristics, large inland lakes and topography[10].

Processes like equatorial and coastal wind driven upwelling, riverine input, vertical mixing and stability, are related to the location of the ITCZ and influence coastal and ocean interior nutrient cycles, biological productivity, and biodiversity [19]. The short rainy season is generally associated with a greater inter annual variability as the migration of the ITCZ tends to be more swift on its return south. The dominating winds are from the North-East and humidity comes from air masses humidified by the Indian Ocean and Lake Victoria[20].

The dry season that follows (January to end February) is characterised by the penetration in East Africa by dry and cold air masses from the Arabian Dorsal.
However, the moderating effect of Lake Victoria and the diversity of the Rwanda's relief maintain some rainfalls in the country[8][21].

2.2.2 El Nino Southern Oscillation (ENSO)

This is an irregularly periodic variation in winds and sea surface temperatures over the tropical Pacific Ocean. It affects the climate of much of the tropical and subtropical regions.
The warming phase of sea surface is termed El Nino (positive phase) and is accompanied by high surface air pressure leading to increased evaporation and thus rainfall while the cooling phase is called La Nina (negative phase) and is accompanied by low surface air pressure in tropical western Pacific Ocean.

The two phases relate to the walker circulation. When the walker circulation weakens or reverses, an El Nino results and causes the ocean surface to be warmer than normal, as upwelling of cold water is not significant. An especially strong walker circulation causes La Nina, resulting in cooler ocean due to increased upwelling. ENSO events are in general associated with an anomalous enhancement of rainfall primarily between 5 °S to 15 °N and a reduction to the south of 5 °S[22]**.**
Rainfall anomalies in eastern Africa have been linked to the influence of ENSO (El Niño-Southern Oscillation) and the IOD (Indian Ocean Dipole). IOD is an interannual mode of variability in Indian Ocean SST that is characterised by perturbation in zonal gradient of SST and anomalous low-level winds. It is an anomalous state of the ocean-atmosphere system [23] [24].

The strength of the IOD is measured in terms of the dipole mode index (DMI), which is the difference in SST anomalies between the Tropical Western (50^0E – 70^0E, 10^0S – 10^0N) and Southeastern (90^0E – 110^0E, 10^0S – 0^0) Indian Ocean parts. The DMI varies between −1 and 1.5˚C with a standard deviation of 0.3 [23][25]. Indian Ocean Dipole (IOD) index plays an important role in shaping the weather conditions in the Indian Ocean and surrounding areas[26] [27].

The October to December season in East Africa is strongly affected by complex interaction between the Indian and Pacific Oceans (IOD-ENSO respectively) and exhibits higher inter annual variability than March to May season[28].
Generally, dry periods over Rwanda and East Africa as a whole are linked to La Nina or negative Indian Oscillation Dipole events while wet periods are associated to El Nino and/or positive IOD events[4][11][12] [16] [29].

The positive phase of the IOD is associated with warm SST in the Tropical Western Indian Ocean and cold SST in Tropical Southeastern Indian Ocean.

Wet periods are characterised by rising motion of moisture containing air masses while dry periods are marked by sinking motions and spreading of moisture divergence anomaly near the surface.
Saji and Yamagata, 2003 as well as Owiti *et al.*, 2008 showed that the IOD influence to the regional rainfall is greatest when coupled with positive ENSO events during the short rain season.
However, extreme events such as the East African floods were driven purely by the IOD [30]. Rao *et al.*, (2002) has identified that about 30% of positive IOD episodes co-occur with El Niño events. Reports on positive IOD show marked easterly moisture anomalies along the equator and the western Indian Ocean resulting in enhanced rainfall over EA region [24]. Recent GCM simulation studies like [31] lead to conclusions that 48%(38%) of extremely high amounts of short rains are recorded in the presence(absence) of ENSO forcing.

2.2.3 Monsoon

Monsoons are organized wind patterns that flow and change directions based on thermal differences between land and ocean air masses. They are weather systems resulting from land-sea temperature differences caused by solar radiation.
Over East Africa, two monsoons are observed; the winter or northeast (NE) monsoon during December to February and summer or southeast (SE) monsoon during June to August [32].

The two monsoons usually influence climatic conditions over East Africa. Usually, the northeast monsoon is warm and dry and occurs during Southern Hemisphere summer. On the other hand, Southeast monsoon is cool and moist and occurs when the sun is at the north of the equator. It picks the maritime moisture from Indian ocean and induces precipitations over some sub regions of east Africa.

The peak monsoon months (e.g., July-to-September and December-to-February) correspond to the dry seasons in the region. This is because monsoons are thermally stable, and associated with subsiding air becoming relatively dry. This partly accounts for the relatively arid conditions in much of the region[33].

2.2.4 Sub-tropical anticyclones

These are synoptic scale quasi-permanent high pressure cells characterised by anti-cyclonic circulation which gives rise to subsidence and low level horizontal velocity divergence of air masses. The major anticyclones which influence the movement of winds over the region are; the St. Helena high pressure system at the Atlantic Ocean south-west, the Mascarene high pressure system at the south-east of Indian Ocean, the Arabian high in the middle east and Azores high pressure system. The later controls the position and the movement of ITCZ as well as the Congo air mass regime over the central and south-east of Africa[7].

Mascarene anticyclones from eastern cost of South Africa converge with wet winds. Saint Helena anticyclones, from the south Atlantic Ocean pass over the Congo basin and through lake Kivu to form ITCZ. This results in heavy rainfall over Rwanda during MAM. For JJA period, the climate of Rwanda is dry mainly in Eastern lowlands and is influenced by dry anticyclones of Saint Helena and Azores while the western highlands receive some rainfall resulting from Saint Helena anticyclones passing over lake Kivu from Atlantic Ocean[7].

2.2.5 Tropical cyclones

The cyclones are low pressure centers where air masses meet and rise. Tropical cyclones (TCs) and their remnants are significant drivers of precipitation in different continental locations across the tropics and mid latitudes[34].

Some studies showed that the spatial distribution of TC rainfalls is influenced significantly by various environmental conditions such as humidity, TC motion induced by steering flow, vertical wind shear, planetary vorticity and topography[35].

The tropical cyclones that influence weather in eastern and southern Africa form in the West Indian Ocean equator-ward at 20^{o} latitude North of the equator. These usually form in the northern spring and late fall and move northwards into the Arabian Sea. Over East Africa, their influence is significant from December to April.

2.2.6 Local systems

Even though it is located in the tropical belt, Rwanda experiences a temperate climate due to its high elevation. The north-western and volcanic parts are of high altitude of over 2000m. The elevation reduces towards the central plateau (1500 - 2000m) and then again in the eastern plateau (less than 1500m). Orographic lifting enhances convective rainfall in the western highlands[15] and this reduces progressively on the move to the east.

The Congo air mass is humid, thermally unstable and therefore associated with rainfall. The Congo air mass significantly boosts convection and overall rainfall amounts received, especially over the western and northwestern parts of the Lake Victoria basin[33].

2.3 Climate projections

The purpose of climate projection is to predict the future state of climate at a given location so that users or the public can plan their activities accordingly.

Over recent decades, the development of numerical models able to simulate atmospheric, oceanic, or other geophysical processes increasingly became a major focus of scientific researchers. An important aspect of the model development process is the evaluation of its performance[36].

This is done by determination of the model accuracy, i.e. the extent to which model-predicted events approach a corresponding set of observations (measured) and precision, i.e., the degree to which model-predicted values approach a linear function of the corresponding observations, and the extent to which the model behaves with respect to prevailing scientific theories. This is referred to as operational and scientific evaluation of the model[36].

Often the operational evaluation of precision and accuracy provide the most tangible means of establishing model credibility. This is the reason why the development, examination, and recommendation of methods used to determine and compare the accuracy and precision of models are of primary concern[36].

The projection of rainfall over Rwanda is of outermost importance as it helps in understanding the expected changes, to predict the impacts of their changes and variability.

Over recent decades, changes in climate have caused impacts on human and natural systems on all continents. It is projected that extreme rainfall events will become more intense and frequent in the future[37].

From the view that local climate results from large-scale atmospheric characteristics and local-scale systems, varied techniques intended to provide climate change information at scales more relevant to decision makers have been developed. However, the climate information still contains uncertainties incorporated in the prediction process, and users must take them into account when using the information.

2.3.1 Rainfall Projection techniques

Global climate models (GCMs) have resolutions of hundreds of kilometers while regional climate models (RCMs) may be as fine as tens of kilometers. However, many impact applications require the equivalent of point climate observations and are highly sensitive to fine-scale climate variations that are parametrized in coarse-scale models.

GCMs provide only a broad view of how climate variables, such as global temperature and rainfall patterns, might change in the future in response to rising concentrations of anthropogenic greenhouse gases. They cannot resolve important processes relating to sub grid scale like clouds and topographic effects that are of significance to many impact studies[38].

To obtain rainfalls to be used in local impact studies, downscaling techniques are recommended. Downscaling is the process of making the link between the state of large-scale variable representing a large space and the state of small-scale variable representing a much smaller space. It usually refers to an increase in spatial or temporal resolution.

The large-scale variable may for instance represent the circulation pattern over a large region whereas the small scale may be the local precipitation.

The large-scale variable varies slowly and smoothly in space while the small-scale variable may be a reading from a thermometer, barometer or the measurement made with a rain gauge[39].

The two main approaches to downscaling climate information are dynamical and statistical. Dynamical downscaling requires running high-resolution climate models on a regional sub-domain, using observational data or lower-resolution climate model output as boundary condition. It relies on the use of a regional climate model (RCM), similar to a GCM in its principles but with high resolution by incorporating boundary conditions such as complex topography, the land-sea contrast, surface heterogeneities, and detailed descriptions of physical processes in order to generate realistic climate information at a spatial resolution of approximately 20–50 kilometers[40].

Statistical downscaling is a two-step process wherewith statistical relationships between local climate variables and large scale predictors are developed and are applied to the output of Global Climate Model (GCM) experiments to simulate local climate characteristics in the future.

Local climate variables are for example the precipitation and surface air temperature while large scale predictors are pressure fields, etc. Statistical Downscaling is more advantageous as it is relatively easy to produce. It can provide station-scale climate information needed for institutions that do not have high computational capacity and technical expertise required for dynamical downscaling.

When using statistical downscaling, assumptions like the fact that the statistical relationship between the predictor and predictand remains stable over time, the large-scale variable represents the climate system and captures any change that may occur in the future, the strength of the relationship is initially evaluated to determine its validity and the ability of a GCM to simulate climate variables observed in the past as well as their future evolution have to be taken into account[40].

2. 3. 2 CORDEX data and rainfall simulation

Due to the fact that dynamical downscaling is computationally expensive, many projects are used to generate climate simulations by model inter-comparisons. These projects include the Coordinated Regional Climate Downscaling Experiment (CORDEX) that produces dynamically downscaled climate simulation for all continents. It should be noted that all CORDEX RCMs are set to 0.44˚ by 0.44˚ spatial resolutions corresponding to about 50 km by 50 km.

CORDEX is a program sponsored by World Climate Research Program(WRCP) to develop an improved framework for generating regional-scale climate projections for impact assessment and adaptation studies worldwide within IPCC AR5 timeline and beyond.

The study using RCMs from CORDEX to simulate rainfall characteristics over Mbarali River Catchment in the Rufiji Basin, Tanzania, has indicated a better performance to reproduce the rainfall characteristics. The average of ensemble of models performed better than individual models in representing rainfall[41].

The evaluation of models showed a better performance of RCMs from the Coordinated CORDEX to simulate rainfall over Tanzania, however, it under estimates and overestimates the amount of rainfall during MAM and OND seasons respectively [42].

The evaluation of the ability of CORDEX RCMs in simulating monthly rainfall variation during the austral summer half year (October to March) over southern Africa has indicated that RCMs adequately capture the reference precipitation probability density functions, with a few showing a bias towards excessive light rainfall events[43].

It was found that most RCMs reasonably simulated the rainfall climatology over the three sub-regions and also reproduced the majority of the documented regional responses to ENSO and IOD forcing. At the same time, it was shown that significant biases in individual models depends on sub-region and season; however, the ensemble mean has better agreement with observation than individual models[44].

In general, it was found that the multimodal ensemble mean simulates eastern Africa rainfall adequately and can therefore be used for the assessment of future climate projections for the region[44].

CORDEX promote international downscaling coordination and facilitate easier analysis by scientists and end-user communities at the local level of regional climate changes. It aims at producing an ensemble of multiple downscaling models considering forcing GCMs from the CMIP5 archive and favouring engagement of wider community. It is designed for Africa and has ten RCMs.

On the use of CORDEX to Project rainfall for the Greater Horn of Africa, it has been noted that most of the RCMs reasonably simulate the main features of the rainfall climatology and also reproduce ENSO and IOD signals. Significant biases were observed in individual model but the ensemble mean showed better agreement with observations. In general, the analysis demonstrated that the multimodel ensemble mean is better to simulate regional rainfall adequately and this serves as a motivation for their use for future climate projections[45].

CHAPTER 3: METHODOLOGY

3.1. Data and Methodology

3.1.1 Data

Historical data for this research were produced by different downscaling groups which belong to CORDEX Africa. These data were provided at the daily time scale for the period of 1951 to 2100 and the reference period for bias correction being 1961 to 1990. Prior to use, the data were processed and converted to monthly and then to seasonal data. 1961 to 1990 period served as a basis for correlation analysis in this research. Seasonal rainfall patterns were analysed and projected.

The observed data were collected from Rwanda Meteorology Agency (Meteo Rwanda). Rainfall data are developed by Meteo Rwanda in partnership with International Research Institute for Climate and Society (IRI). Gridded Rainfall data from 1961 to 1990 for the selected seven stations were used to find projected rainfalls over Rwanda in the future.

Regional climate scenarios for Africa are available on a grid of 0.44 degrees, approximately 50km spatial resolution at the equator. The methodology of this research consisted of a two-step process; namely the development of statistical relationships between observed precipitation data from meteo Rwanda and simulated precipitation data from CORDEX Africa RCMs resulting in a regression line and the application of such relationship (regression line) to project rainfall over Rwanda in the future.

3.1.2 Methodology

To achieve the objective of this study, the method used is spatial and temporal analysis as well as climate projection over Rwanda.

3.1.2.1 Temporal and Spatial Analysis

For temporal analysis, monthly rainfalls were used to determine the seasonal rainfall climatology. Temporal variability of rainfall was investigated using a time series analysis. Plotting of time series involved rainfall data and time. The seasonal climatology for each selected station was computed and subjected to a time series analysis.

Stations were selected so as to cover all rainfall zones of Rwanda. Table 3 shows a number of seven selected stations and their respective locations (Longitudes and Latitudes)

Table 1: List of rainfall stations considered and their locations

Source: [15]

N^{o}	**Station**	**Latitude**	**Longitude**
1	KIGALI	1.95^{o}S	30.12^{o}E
2	NGOMA	2.17^{o}S	30.53^{o}E
3	NYAMAGABE	2.47^{o}S	29.57^{o}E
4	BYUMBA	1.58^{o}S	30.07^{o}E
5	KAMEMBE	2.47^{o}S	28.92^{o}E
6	RUBAVU	1.67^{o}S	29.25^{o}E
7	NYAGATARE	1.29^{0}S	30.33^{0}E

Excel and Python programs were used in plotting time series trends.

3.1.2.2 Assessing the performance of CORDEX to simulate the climate of Rwanda

In this study, a combination of graphic and statistical methods was used to assess the performance of CORDEX to simulate the climate of Rwanda. CORDEX data for Rwanda are available to a grid of 0.44 degrees corresponding to almost 50km to 50km spatial resolution. Statistical methods were used to check the accuracy and bias of the available data compared to the observed data[36][46][47]. Comparison between rainfall data from CORDEX RCMs and observed rainfall data from Meteo Rwanda was done to test the ability of CORDEX to reproduce the seasonal cycles and inter annual variability of rainfall trends.

Checking the performance and simulation of statistical models before use to project climate of a region is more important as the performance of the statistically downscaled data differs from location to location and from one RCM to another.

Statistical measures of model performance such as root mean square error (RMSE), Pearson correlation coefficient, mean absolute error (MAE) and mean bias error (MBE) were used to test the absolute scalar accuracy measure[36]. The statistical significance was reported by combining different statistical parameters.

The mean absolute error (MAE) is the arithmetic average of absolute differences between the observed (Oi) and predicted (Pi) values. It is expressed as:

$$MAE = \frac{1}{n}\left[\sum_{i=1}^{n} |Pi - Oi|\right]$$

With n, the number of observations, Pi the predicted value, and Oi the observed value. For perfect prediction, the MAE ranges between zero and large positive values[36].

The RMSE is the square root of average squared differences between Pi and Oi. The square function in the RMSE makes the measure to be more sensitive to extreme errors than the MAE measure[48]. It is expressed as:

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{Pi} - \mathrm{Oi})^2}$$

With n, the number of observations, Pi the predicted value, and Oi the observed value

The MBE is the average of the differences between the Predicted (Pi) and Observed (Oi) pairs. MBE indicates an average interpolation bias which is an average over or under-estimation by an interpolator[46]. A value close to zero indicates equal distribution between negative and positive errors. It is expresses as:

$$MBE = \frac{1}{n}\left[\sum_{i=1}^{n} Pi - Oi\right]$$

With n, the number of observations, Pi the predicted value, and Oi the observed value.

Since the MBE averages the sum of errors, it does not give a better indication of the magnitude of individual prediction errors [48].

The index of agreement (d) will be calculated as follows[36]:

$$d = 1 - [\frac{\sum_{i=1}^{n}(Pi - Oi)^2}{\sum_{i=1}^{n}(|Pi - p| + |Oi - o|)^2}]$$

With n, the total number of observations, Pi the predicted value, Oi the observed value, while p and o are the means of the predicted and observed values, respectively. The relative accuracy measure ‘d’ accounts for the differences between means and variances of Pi and Oi. It ranges between 0.0 and 1.0. Values close to 1.0 indicates better agreement between the Oi and Pi [46].

The correlation coefficient (r) is calculated using this formula [49]

$$r = \frac{cov(O,M)}{\sigma O \sigma M}$$

where cov and σO, σM represent the covariance and the standard deviation of O and M. O and M represent respectively the observed and the projected rainfall time series.
The coefficient of variation is calculated as follows

$$Cv = 100 * \frac{\sigma}{\mu}$$

where σ and μ are respectively the standard deviation and the mean of the observed or the projected rainfall for the considered period. The above parameters were used to assess the performance of CORDEX RCMs in simulating rainfall over Rwanda and to validate the RCMs to be used in projection.

3.1.2.3 Rainfall projection

Once the better performing CORDEX RCM is validated, the last step of the process consisted in projection of rainfall over Rwanda. The period of interest is 2021 to 2050.

A regression equation showing the relationship between the simulated and observed rainfall data was computed and used for projections[50]. It is of the form y = ax + b where a and b are constants, x is the projected value and y is the corrected value corresponding to future rainfall at a particular station obtained by a particular RCM. Projection were done under RCP4.5 and RCP8.5 scenarios.

Comparison between rainfall data from CORDEX RCMs and observed rainfall from Meteo Rwanda was done to test the ability of CORDEX to reproduce the seasonal and interannual variability of rainfall trends over Rwanda.

After evaluation of all available GCMs, namely CNRM-CM5, ICHEC-EC-Earth, MOHC-HadGEM2-ES and MPI-ESM-LR models and the corresponding two RCMs which are RCA4 and CLMcom from CORDEX Africa, for almost all the seven stations, CLMcom driven by CNRM-CM5 showed a better performance compared to others. The above set of GCMs was assessed in previous studies over South and East Africa and provided useful information on rainfall projections for the region[51][45][41].

In general RCMs simulate the precipitation seasonal mean and annual cycle accurately, although individual models can exhibit significant biases in some sub regions and seasons[52].

The rainfall projection over Rwanda was done using CLMcom driven by CNRM-CM5. For further readings, detailed literature on different CORDEX RCMs models can be found in [53][54][55][56][57] [58][59] [60][61].

CHAPTER 4: RESULTS PRESENTATION AND DISCUSSIONS

In this chapter we present the research findings and the corresponding methods used to reach the set objectives. The performance of CORDEX in simulating rainfall over Rwanda, spatial and temporal variation of rainfall and future rainfall projections have been achieved. Eight models were tested and one of them was found to be the best in simulating rainfall patterns and variability for most of the seven considered stations.

4.1 Model performance evaluation

As described in the previous chapter, before rainfall projections over Rwanda, different models were tested for accuracy and the more performing model was validated and then used for projections of rainfall trends in the future. Statistical measures like the Root Mean Square Error, the Mean Absolute Error, the Mean Bias Error, the correlation coefficient and index of agreement have been used together with graph presentations of model data against station observations.

Graphical methods for model validation have an advantage over numerical methods as they readily illustrate complex aspects of the relationship between the data and model while numerical methods tend to focus on a particular aspect and try to compress the information into a simple description.

The best performing model is CLMcom driven by CNRM-CM5 as it was found to have lower errors (RMSE and MAE), significant correlation coefficient (r and thus r^2) and higher index of agreement(d) values.

Numerical methods played a confirmatory role to graphical methods. The more performing model results have been corrected and finally, a regression equation intended to be used in projections has been computed. Statistically calculated measures at particular stations on annual and seasonal basis are tabulated in addendum I.

Model performance has been evaluated on monthly, seasonal and annual basis. The next sections describe the whole process and presents some of the seasonal and annual statistics used.

4.1.1 Correlation coefficient and coefficient of determination

The correlation coefficient (r) shows the relationship between the predicted data and observed values. It has an upper bound of 1, indicating a perfect positive linear correlation and a lower bound of -1, corresponding to negative linear correlation. A model demonstrates a high capability of rainfall simulation when its correlation coefficient is high.

The coefficient of determination (r^2) measures the proportion of variation that is explained by the model. Ideally, r^2 lies between 0 and 1. When it equal to one, this indicates zero error.

4.1.2 The index of agreement

The index of agreement helps overcome the insensitivity of the coefficient of determination to differences in the observed and model variances and means. It describes the overall relative degree to which observational data approach model data[62]. Although, due to the squaring of the difference terms in calculation of the index of agreement, high values can also be obtained for poor models.

4.1.3 Root Mean Square Error(RMSE) and Mean absolute error (MAE)

The Root Mean Square Error(RMSE) is a quadratic scoring rule which measures the expected magnitude of error associated with a model's prediction. Since the errors are squared before they are averaged, the RMSE gives a relatively high weight to large errors[63].

The Mean Absolute Error(MAE) in contrast measures the average magnitude of the errors in a set of analysis, without considering their direction. It measures the accuracy for continuous variables. It is a linear score, which means that all the individual differences are weighted equally in the average[63].

The MAE and RMSE can be used together to diagnose the variation in the errors in a set of analysis. The RMSE is always larger than or equal to the MAE. The greater the difference RMSE–MAE, the greater the variance in the individual errors in the sample. When all the errors are of the same magnitude, then RMSE = MAE[64].

The Mean Bias Error (MBE) is variable which indicates the direction of the expected model error, and is a measure of a model's tendency towards overestimation or underestimation[65].

In statistics, we should indicate both the model performance measure and the error distribution. The MAE represents well the uniformly distributed errors while model errors have often a normal distribution and are best represented by RMSE [66].

Tables below summarise the model performance on basis of the calculated values of RMSE and R^2 (Table 2), index of agreement and MBE (Table 3) for Annual, MAM and OND seasons at different stations.

Table 2: Coefficient of determination and RMSE at different stations for Annual, MAM and OND seasons

		Annual		**MAM**		**OND**	
		R^2	**RMSE**	**R^2**	**RMSE**	**R^2**	**RMSE**
Kigali	**RCP 4.5**	0.43	226.34	0.19	132.48	0.06	73.24
	RCP 8.5	0.29	239.84	0.06	147.87	0.07	66.52
Kamembe	**RCP 4.5**	0.004	201.86	0.08	99.88	0.12	96.5
	RCP 8.5	0.004	211.86	0.08	102.81	0.12	104.03
Gicumbi	**RCP 4.5**	0	273.2	0.03	180.96	0.16	128.1
	RCP 8.5	0	276.18	0.03	180.95	0.16	127.91
Ngoma	**RCP 4.5**	0.182	196.65	0.036	116.3	0.002	78.93
	RCP 8.5	0.175	194.74	0.041	115.3	0.002	78.42
Rubavu	**RCP 4.5**	0.03	404.03	0.007	181.55	0.012	174.55
	RCP 8.5	0.03	402.90	0.006	176.68	0.011	169.99
Nyagatare	**RCP 4.5**	0.18	185.5	0.06	128.4	0.02	80.7
	RCP 8.5	0.07	186.9	0.06	128.6	0.02	82.1
Nyamagabe	**RCP 4.5**	0.02	290.55	0.05	156.9	0	98.54
	RCP 8.5	0.02	292.24	0.04	158.07	0	99.49

Table 3: Index of agreement and MBE at different stations for Annual, MAM and OND seasons

		Annual		**MAM**		**OND**	
		Index	**MBE**	**Index**	**MBE**	**Index**	**MBE**
Kigali	**RCP 4.5**	0.99	4.96	0.96	-8.15	0.99	37.91
	RCP 8.5	0.98	41.25	0.96	34.41	0.99	29.34
Kamembe	**RCP 4.5**	0.99	-12.79	0.99	23.23	0.99	18.06
	RCP 8.5	0.99	11.86	0.99	27.56	0.99	29.69
Gicumbi	**RCP 4.5**	0.99	-92.39	0.96	-124.18	0.97	-1.97
	RCP 8.5	0.99	-98.3	0.96	-124.25	0.97	-9.97
Ngoma	**RCP 4.5**	0.98	-5.002	0.97	-23.46	0.98	12.618
	RCP 8.5	0.98	3.377	0.97	-19.65	0.98	14.179
Rubavu	**RCP 4.5**	0.97	280.77	0.95	93.01	0.95	124.43
	RCP 8.5	0.97	279.65	0.96	89.73	0.95	118.82
Nyagatare	**RCP 4.5**	0.99	59.6	0.96	21.5	0.98	38.2
	RCP 8.5	0.99	65	0.96	23.4	0.98	40.2
Nyamagabe	**RCP 4.5**	0.98	-36.09	0.97	-33.62	0.98	41.38
	RCP 8.5	0.98	-27.94	0.97	-25.19	0.98	41.51

In general, the model reproduces the same trends representing Annual, MAM and OND historical data all over the country although it underestimates rainfall over Gicumbi station for annual and MAM seasons and overestimates the rains of Rubavu station for all seasons.

4.2. Spatial and temporal rainfall variability over Rwanda

Rainfall over Rwanda is not equally distributed over sub regions. The pattern is the increase in rainfall with elevation. The actual mean seasonal and annual rainfall has been computed for the stations considered in this study. Table 4 presents the obtained results.

Table 4: Mean rainfall (mm) for long rain (MAM); short rain (OND) and Annual Rainfall

Station	**Annual**	**MAM**	**OND**
Kigali	1029.26	391.62	318.99
Kamembe	1445.75	457.5	490.68
Gicumbi	1381.49	558.56	429.33
Ngoma	1000.63	405.06	313.5
Rubavu	1175.69	384.52	356.13
Nyagatare	883.9	321.5	287.2
Nyamagabe	1291.4	496.3	373.7

4.3 Rainfall projection over Rwanda

Before projections, validated model has been bias corrected to reduce the errors and the resulting values have been plotted to show future trends in rainfall over Rwanda.

The linear regression line of the form **y = ax + b** has been computed between the observed station data and the historical model data during annual, MAM and OND seasons and those coefficients were used to find the projected rainfalls. Table 5 summarises the obtained values of a and b, the regression line coefficients.

Table 5: Regression line coefficients for annual, MAM and OND seasons

Station	**Scenario**	**ANNUAL**		**MAM**		**OND**	
		a	**b**	a	b	a	b
KIGALI	RCP 4.5	-0.641	1677.7	-0.389	526.1	0.260	279.1
	RCP 8.5	-0.599	1675.8	-0.269	527.0	0.263	267.9
KAMEMBE	RCP 4.5	-0.166	1727.3	0.144	384.6	0.329	386
	RCP 8.5	-0.157	1727.5	0.130	391.5	0.379	376.1
GICUMBI	RCP 4.5	0.029	1246.1	0.100	362.0	0.194	334.7
	RCP 8.5	0.032	1232.3	0.099	361.9	0.185	328.3
NGOMA	RCP 4.5	-0.322	1311.9	-0.140	420.7	0.030	323.5
	RCP 8.5	-0.312	1311.1	-0.147	427.7	0.027	326
RUBAVU	RCP 4.5	-0.154	1721.7	-0.073	539.6	0.154	454.6
	RCP 8.5	-0.154	1717.6	-0.063	531.3	0.152	447.8
NYAMAGABE	RCP 4.5	0.089	1134.5	0.143	391.1	-0.005	415.8
	RCP 8.5	0.084	1150.9	0.145	399.7	-0.016	420.1
NYAGATARE	RCP 4.5	-0.031	999.7	-0.157	403.6	-0.105	363.9
	RCP 8.5	-0.020	995.4	-0.153	403.8	-0.104	367

The above regression line coefficients were used to compute the projected rainfall changes on annual, MAM and OND decadal and climatology basis. Tables 7 to 10 in addendum II present decadal and climatology future rainfall changes.

Projected rainfall changes at different stations and periods are presented in Figures 3 to 10 below

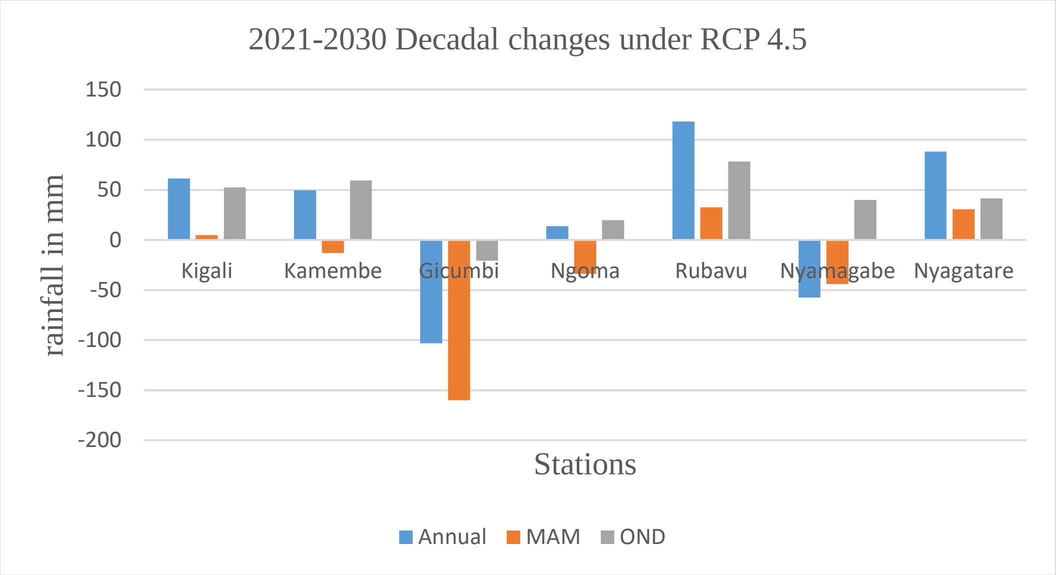

Figure 3: Projected 2021-2030 decadal rainfall change under RCP4.5

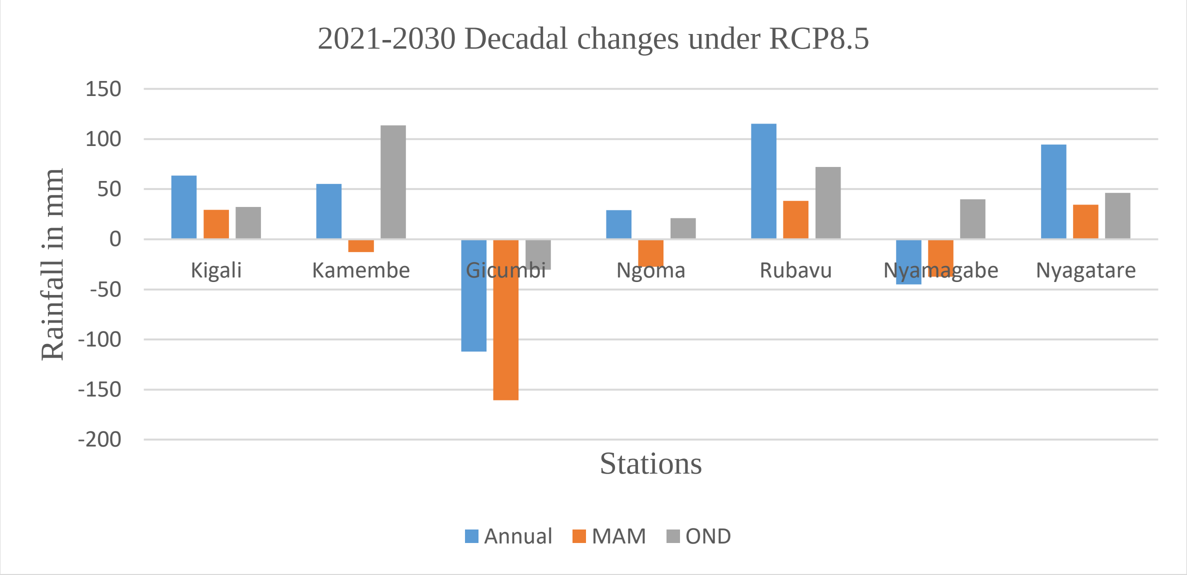

Figure 4: Projected 2021-2030 decadal rainfall change under RCP8.5

Under the two scenarios, a general rainfall increase is projected. The decreasing pattern is projected at Gicumbi for all seasons, Nyamagabe for annual and MAM, Ngoma and Kamembe for MAM. The highest OND rainfall is projected at Rubavu for RCP4.5 while it is projected at Kamembe under RCP8.5.

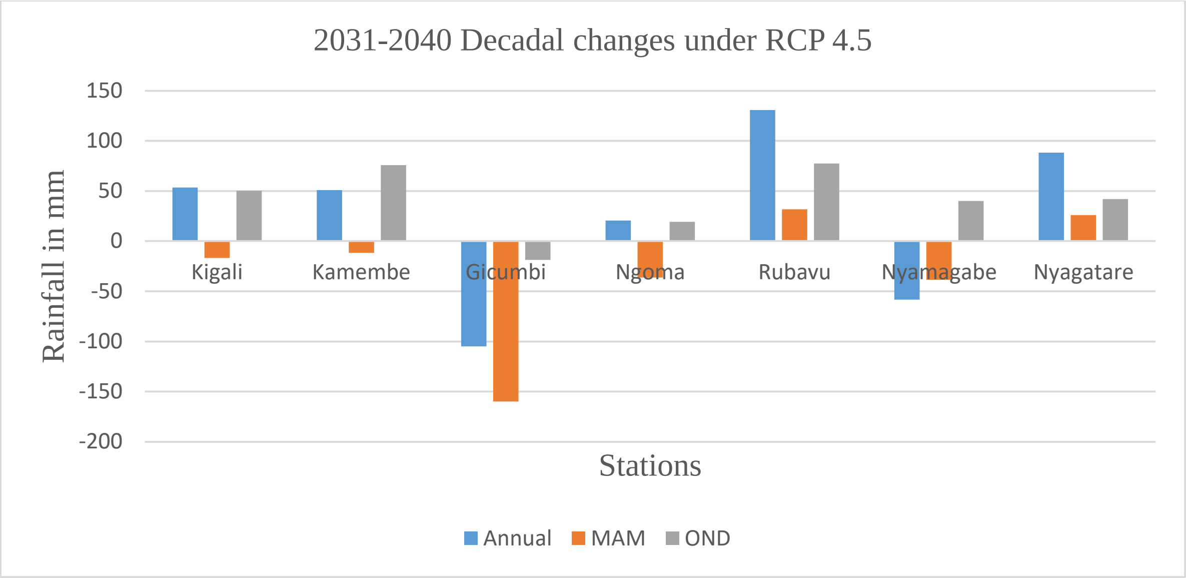

Figure 5:Projected 2031-2040 decadal rainfall change under RCP4.5

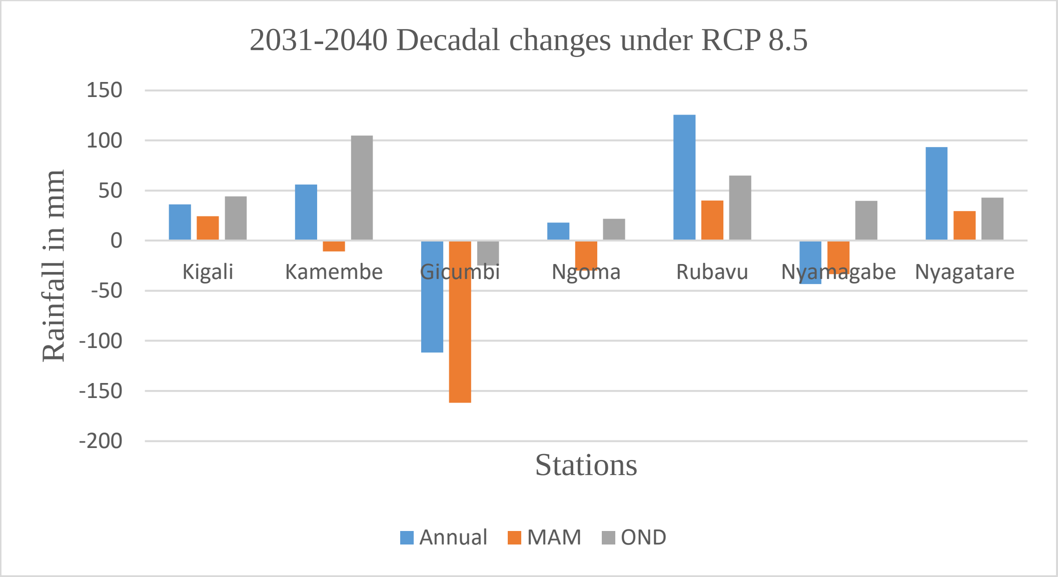

Figure 6: Projected 2031-2040 decadal rainfall changes under RCP8.5

Rainfall increase is projected in general for annual and OND. The decreasing pattern is projected at Gicumbi for all seasons, Nyamagabe for annual and MAM and Ngoma and Kamembe for MAM. A decrease in rainfall at Kigali station is projected under RCP4.5.

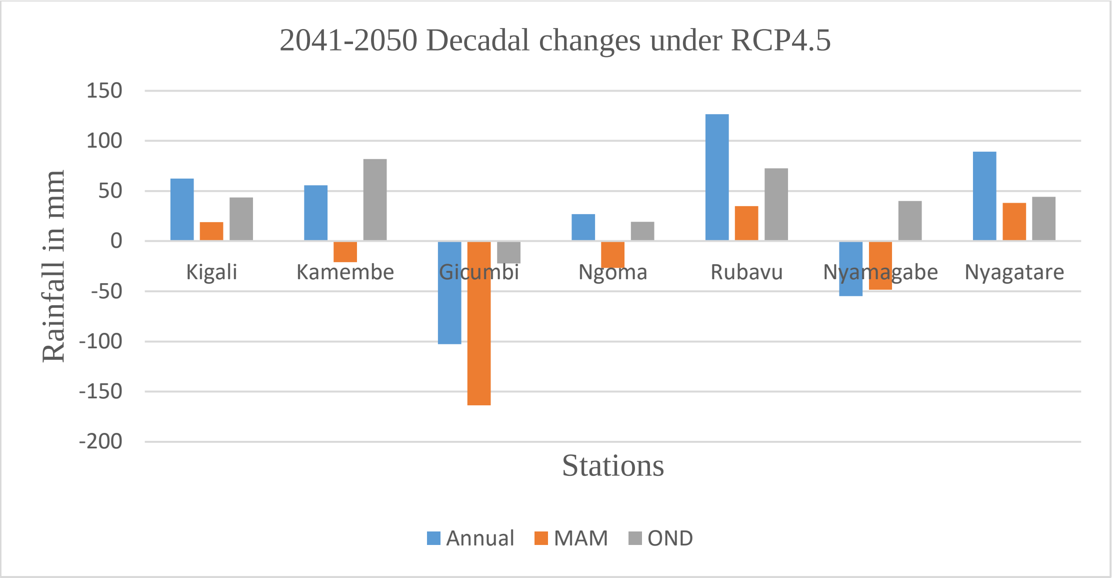

Figure 7: Projected 2041-2050 decadal rainfall change under RCP4.5

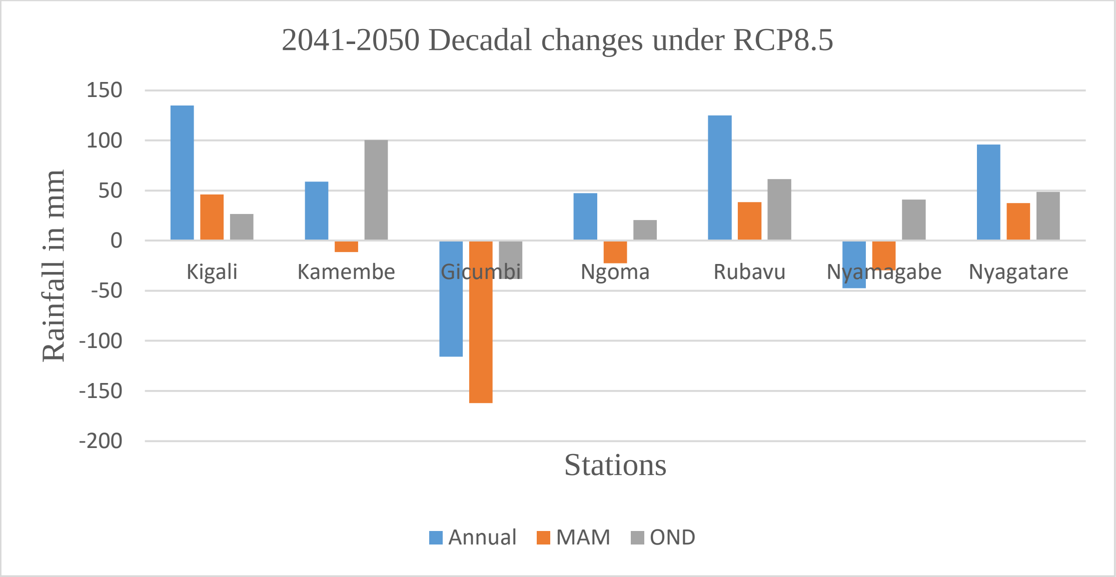

Figure 8: Projected 2041-2050 decadal rainfall change under RCP8.5

There is a projected general rainfall increase at almost the whole country. The decreasing pattern is projected at Gicumbi for all seasons and Nyamagabe for annual and MAM as well as Ngoma and Kamembe. Extreme annual rainfall is projected at Rubavu and Kigali stations. Kamembe station will experience the highest OND rainfall.

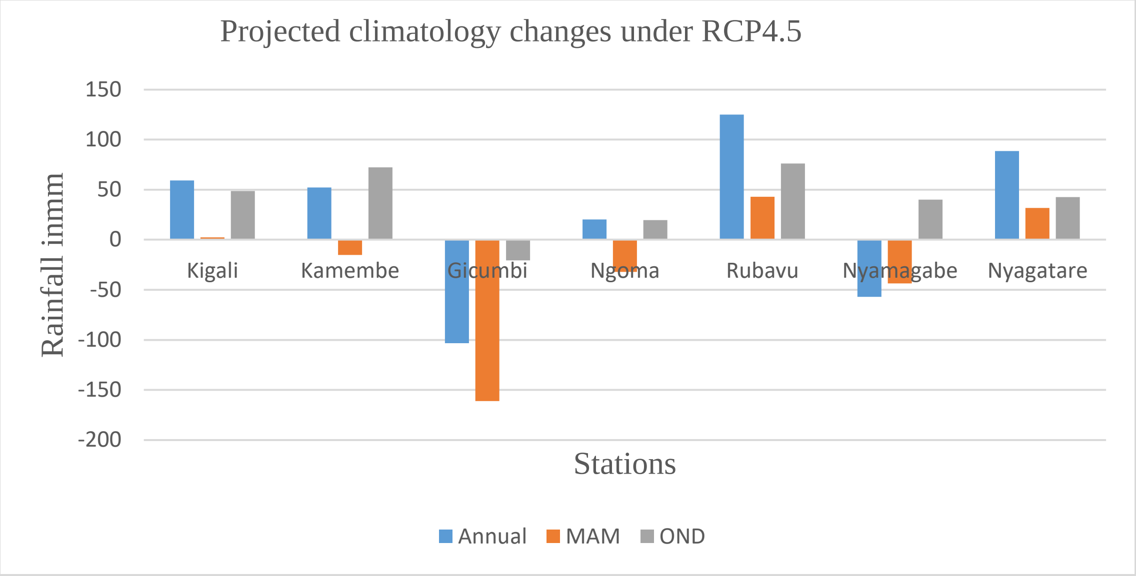

Figure 9: Projected 2021-2050 Climatology rainfall change under RCP4.5

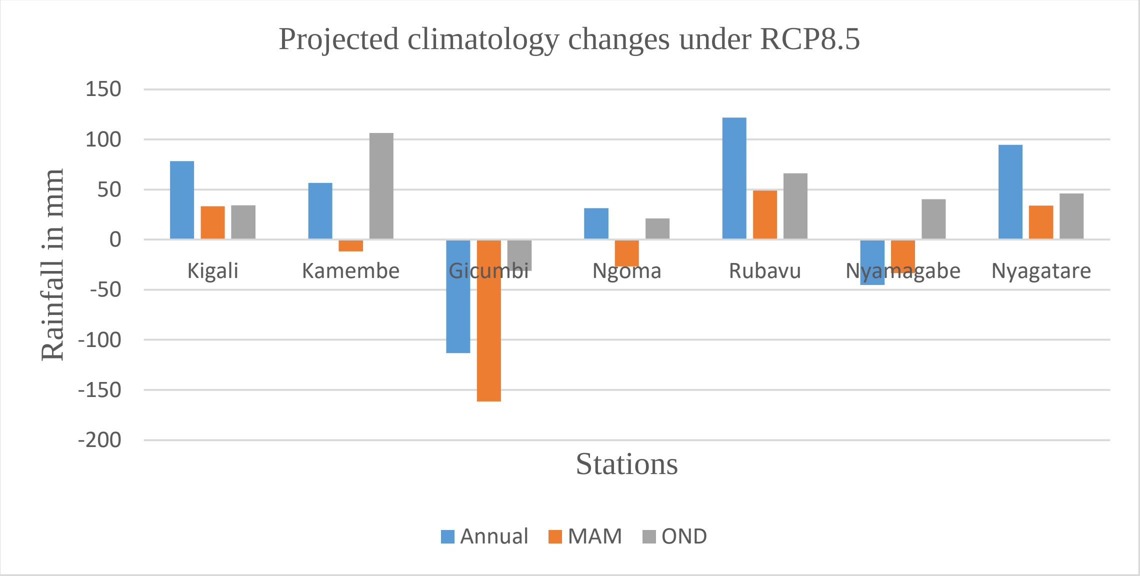

Figure 10: Projected 2021-2050 Climatology rainfall change under RCP8.5

From the climatological rainfall projection graph, we can note the following:

Under the two scenarios, the annual rainfall will increase except for Gicumbi and Nyamagabe stations. MAM rainfall is projected to decrease for four of the seven stations while OND rainfall shows an increasing pattern with the exception of Gicumbi station.

There is consistency of rainfall increase for Rubavu station and a decrease at Gicumbi station under both scenarios. Previous researches observed the same patterns[44]

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

In this research, we investigated the performance of CORDEX in simulating the climate of Rwanda, especially rainfall, we projected seasonal rainfall variability over Rwanda and found the projected changes in rainfall climatology for annual, long and short rain seasons.

Model evaluation and validation were done by graph and statistical methods on two RCMs each driven by four GCMs. After performance test, CLMcom RCM driven by CNRM-CM5 showed a high skill at simulating the climate of Rwanda and it has been used for future projections. A regression line was computed to enable us project seasonal and climatology rainfall over Rwanda using the above model under RCP4.5 and RCP8.5 scenarios.

The projected climatological rainfall patterns show decreasing rainfall under both scenarios at Gicumbi and Nyamagabe stations and a general increasing rainfall pattern over other stations.

A pronounced rainfall increase is projected at Rubavu station for all seasons and both scenarios. The decreasing or increasing extent varies from station to station. Regions with high rainfalls are likely to experience flood and landslide events while region with lower rainfalls may experience droughts.

Due to the limitations of time, we considered a few CORDEX models, so we would like to recommend a deep research on other models' ability to simulate the climate of Rwanda. As the rainfall of Rwanda is highly variable, a regional model adapted over Rwanda domain is recommended to capture all the factors which influence that variability for good projections.

REFERENCES

[1] R. Mahmood and M. S. Babel, “Future changes in extreme temperature events using the statistical downscaling model (SDSM) in the trans-boundary region of the Jhelum river basin,” *Weather Clim. Extrem.*, vol. 5–6, pp. 56–66, 2014.

[2] “Used-Eric M. Laflamme.pdf.” .

[3] E. E. T. Al, R. P. Anitz, and M. B. U. Atthias, “Assessment of the Performance of CORDEX Regional Climate Models in Simulating East African Rainfall,” 2013.

[4] J. P. Ngarukiyimana, Y. Fu, Y. Yang, B. A. Ogwang, V. Ongoma, and D. Ntwali, “Dominant atmospheric circulation patterns associated with abnormal rainfall events over Rwanda, East Africa,” *Int. J. Climatol.*, vol. 38, no. 1, pp. 187–202, 2018.

[5] “Rwanda Country Situational Analysis Compiled by Alphonse Mutabazi Climate Change Consultant For Camco , P . O . Box 76406-00508 Nairobi , Kenya May 2011 Introduction to the Assignment,” no. May, 2011.

[6] J. N. Sebaziga, “Association Between Madden-Julian Oscillations And Wet And Dry Spells Over Rwanda,” 2014.

[7] I. Muhire, F. Ahmed, E. Studies, A. Park, and S. Africa, “Spatio-temporal trend analysis of precipitation data over Rwanda,” no. March 2015, pp. 37–41.

[8] K. Mikova, E. Makupa, and J. Kayumba, “Effect of Climate Change on Crop Production in Rwanda,” vol. 4, no. 3, pp. 120–128, 2015.

[9] D. Ntwali, B. A. Ogwang, and V. Ongoma, “The Impacts of Topography on Spatial and Temporal Rainfall Distribution over Rwanda Based on WRF Model,” no. March, 2016.

[10] B. A. Ogwang, H. Chen, X. Li, C. Gao, T. Prof, and C. Author, “The influence of Topography on East African October to December climate : Sensitivity experiments with RegCM4 Key Laboratory of Meteorological Disaster , Ministry of Education , Nanjing University of E-mail Addresses : bob_ogwang@yahoo.co.uk (Bob Alex Og,” vol. 2014, pp. 1–27, 2014.

[11] S. E. Nicholson, “Climate and Climatic Variability of Rainfall over Eastern Africa,” 2017.

[12] C. C. Mutai and M. N. Ward, “East African rainfall and the tropical circulation/convection on intraseasonal to interannual timescales,” *J. Clim.*, vol. 13, no. 22, pp. 3915–3939, 2000.

[13] P. Sciences, P. Sciences, and E. S. Division, “Regionalizing Africa : Patterns of Precipitation Variability in Observations and Global Climate Models,” pp. 9027–9043, 2016.

[14] L. A. Ogallo, “Dynamics of the East African climate i . Introduction,” vol. 102, no. 1, pp. 203–204, 1993.

[15] N. J. Felix, “CHARACTERISTICS OF EXTREME RAINFALL EVENTS,” no. August, 2015.

[16] C. Megan, “Green Growth and Climate Resilience,” *W. Forw. Int. Clim. Policy*, no. October, p. 100, 2011.

[17] H. Mohammed, C. K. Jean, and W. A. Ahmad, “Projections of precipitation, air temperature and potential evapotranspiration in Rwanda under changing climate conditions,” *African J. Environ. Sci. Technol.*, vol. 10, no. 1, pp. 18–33, 2016.

[18] D. E. Waliser and C. Gautier, “A satellite-derived climatology of the ITCZ,” *Journal of Climate*, vol. 6, no. 11. pp. 2162–2174, 1993.

[19] K. E. Colna, “Latitudinal Position and Trend of the Intertropical Convergence Zone (ITCZ) and its Relationship with Upwelling in the Southern Caribbean Sea and Global Climate Indices,” p. 99, 2017.

[20] C. Carey, M. Cole, and J. Dyszynski, “National Strategy on Climate Change and Low Carbon Development for Rwanda.”

[21] M. O. F. Lands, N. Adaptation, P. Of, and T. O. C. Change, “NAPA-RWANDA,” no. December, 2006.

[22] B. Preethi, T. P. Sabin, J. A. Adedoyin, and K. Ashok, “Impacts of the ENSO Modoki and other Tropical Indo-Pacific Climate- Drivers on African Rainfall,” *Nat. Publ. Gr.*, pp. 1–15.

[23] E. Black, “The relationship between Indian Ocean sea-surface temperature and East African rainfall,” *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 363, no. 1826, pp. 43–47, 2005.

[24] P. N. Vinayachandran, P. A. Francis, S. A. Rao, and O. Sciences, “Indian Ocean Dipole : Processes and Impacts,” no. March 2015, 2002.

[25] O. Zablone and L. Ogalo, “Linkages between the Indian Ocean Dipole and East African Rainfall Anomalies Linkages between the Indian Ocean Dipole and East African Seasonal Rainfall Anomalies,” no. July 2014, 2008.

[26] K. K. Saha and S. A. Wasimi, “Interrelationship between Indian Ocean Dipole (IOD) and Australian Tropical Cyclones,” *Int. J. Environ. Sci. Dev.*, vol. 4, no. 6, pp. 647–651, 2013.

[27] Y. Yang, S. P. Xie, L. Wu, Y. Kosaka, N. C. Lau, and G. A. Vecchi, “Seasonality and predictability of the Indian Ocean dipole mode: ENSO forcing and internal variability,” *J. Clim.*, vol. 28, no. 20, pp. 8021–8036, 2015.

[28] D. Conway, E. Allison, R. Felstead, and M. Goulden, “Rainfall variability in East Africa : Implications for natural resources management and livelihoods Rainfall variability in East Africa : implications for natural resources management and livelihoods,” no. June 2014, 2005.

[29] N. Souverijns, W. Thiery, M. Demuzere, and N. P. M. Van Lipzig, “Drivers of future changes in East African precipitation Drivers of future changes in East African precipitation,” pp. 0–9, 2016.

[30] S. C. Chan, S. K. Behera, and T. Yamagata, “Indian Ocean Dipole influence on South American rainfall,” *Geophys. Res. Lett.*, vol. 35, no. 14, pp. 10–15, 2008.

[31] A. M. Mwanthi, “Investigating Linkages Between the Subtropical Indian Ocean Dipole Mode and East Africa Rainfall During October to December,” 2015.

[32] R. E. Okoola, “A diagnostic study of the eastern Africa monsoon circulation during the Northern Hemisphere spring season,” *Int. J. Climatol.*, vol. 19, no. 2, pp. 143–168, 1999.

[33] M. Kizza, A. Rodhe, C. Xu, H. K. Ntale, and S. Halldin, “Temporal rainfall variability in the Lake Victoria Basin in East Africa during the twentieth century,” pp. 119–135, 2009.

[34] I. City, “Contribution of Tropical Cyclones to Rainfall at the Global Scale,” no. October 1979, pp. 359–372, 2017.

[35] D. Kim, C.-H. Ho, D.-S. R. Park, J. C. L. Chan, and Y. Jung, “The Relationship between Tropical Cyclone Rainfall Area and Environmental Conditions over the Subtropical Oceans,” *J. Clim.*, vol. 31, no. 12, pp. 4605–4616, 2018.

[36] C. J. Willmott *et al.*, “Statistics for the evaluation and comparison of models,” *J. Geophys. Res. Ocean.*, vol. 90, no. C5, pp. 8995–9005, 1985.

[37] IPCC, “Climate Change 2014 Synthesis Report Summary Chapter for Policymakers,” *Ipcc*, p. 31, 2014.

[38] R. L. Wilby, S. P. Charles, E. Zorita, B. Timbal, P. Whetton, and L. O. Mearns, “Guidelines for Use of Climate Scenarios Developed from Statistical Downscaling Methods,” *Analysis*, vol. 27, no. August, pp. 1–27, 2004.

[39] N. De Lay and S. Gottesman, “o Ve rs io n Ve,” vol. 191, no. 2, pp. 1–8, 2009.

[40] S. Trzaska and E. Schnarr, “A review of downscaling methods for climate change projections,” *United States Agency Int. Dev. by Tetra Tech ARD*, no. September, pp. 1–42, 2014.

[41] E. Mutayoba and J. J. Kashaigili, “Evaluation for the Performance of the CORDEX Regional Climate Models in Simulating Rainfall Characteristics over Mbarali River Catchment in the Rufiji Basin, Tanzania,” *J. Geosci. Environ. Prot.*, vol. 05, no. 04, pp. 139–151, 2017.

[42] P. Luhunga, J. Botai, and F. Kahimba, “Evaluation of the performance of CORDEX regional climate models in simulating present climate conditions of Tanzania Evaluation of the performance of CORDEX regional climate models in simulating present climate conditions of Tanzania,” *J. South. Hemisph. Earth Syst. Sci.*, vol. 66, no. March, pp. 32–54, 2016.

[43] M. E. Shongwe, C. Lennard, B. Liebmann, E.-A. Kalognomou, L. Ntsangwane, and I. Pinto, “An evaluation of CORDEX regional climate models in simulating precipitation over Southern Africa,” *Atmos. Sci. Lett.*, vol. 16, no. 3, pp. 199–207, 2015.

[44] H. S. Endris *et al.*, “Assessment of the performance of CORDEX regional climate models in simulating East African rainfall,” *J. Clim.*, vol. 26, no. 21, pp. 8453–8475, 2013.

[45] “Evaluation of the performance of CORDEX RCMs over the Greater Horn of Africa Sub-region In Support of ; Planning for Resilience in East Africa through Policy , Adaptation , Research and Economic Development (PREPARED) Project November 2014,” no. November, 2014.

[46] C. J. Willmott and K. Matsuura, “On the use of dimensioned measures of error to evaluate the performance of spatial interpolators,” *Int. J. Geogr. Inf. Sci.*, vol. 20, no. 1, pp. 89–102, 2006.

[47] M. E. Shongwe, C. Lennard, B. Liebmann, E. Kalognomou, and L. Ntsangwane, “An evaluation of CORDEX regional climate models in simulating precipitation over Southern Africa,” vol. 207, no. October 2014, pp. 199–207, 2015.

[48] D. S. (Department of E. and A. S. C. U. Wilks, *Statistical Methods in the Atmospheric Sciences*, vol. 14. 2006.

[49] A. B. Sarr, M. Camara, and I. Diba, “Spatial Distribution of Cordex Regional Climate Models Biases over West Africa,” vol. 2015, no. September, pp. 1018–1031, 2015.

[50] H. Shiogama *et al.*, “Predicting future uncertainty constraints on global warming projections,” *Sci. Rep.*, vol. 6, no. May 2015, pp. 1–7, 2016.

[51] E. A. Kalognomou *et al.*, “A diagnostic evaluation of precipitation in CORDEX models over Southern Africa,” *J. Clim.*, vol. 26, no. 23, pp. 9477–9506, 2013.

[52] A. Dosio, H. Jürgen, M. Schubert, and F. Daniel, “Dynamical downscaling of CMIP5 global circulation models over CORDEX - Africa with COSMO - CLM : evaluation over the present climate and analysis of the added value,” pp. 2637–2661, 2015.

[53] R. Séférian *et al.*, “Development and evaluation of CNRM Earth system model-CNRM-ESM1,” *Geosci. Model Dev.*, vol. 9, no. 4, pp. 1423–1453, 2016.

[54] R. Knutti, D. Masson, and A. Gettelman, “Climate model genealogy: Generation CMIP5 and how we got there,” *Geophys. Res. Lett.*, vol. 40, no. 6, pp. 1194–1199, 2013.

[55] A. Voldoire *et al.*, “The CNRM-CM5.1 global climate model: Description and basic evaluation,” *Clim. Dyn.*, vol. 40, no. 9–10, pp. 2091–2121, 2013.

[56] T. Koenigk *et al.*, “Arctic climate change in 21st century CMIP5 simulations with EC-Earth,” *Clim. Dyn.*, vol. 40, no. 11–12, pp. 2719–2743, 2013.

[57] T. Koenigk and L. Brodeau, “Arctic climate and its interaction with lower latitudes under different levels of anthropogenic warming in a global coupled climate model,” *Clim. Dyn.*, vol. 49, no. 1–2, pp. 471–492, 2017.

[58] C. D. Jones *et al.*, “The HadGEM2-ES implementation of CMIP5 centennial simulations,” *Geosci. Model Dev.*, vol. 4, no. 3, pp. 543–570, 2011.

[59] V. Brovkin, L. Boysen, T. Raddatz, V. Gayler, A. Loew, and M. Claussen, “Evaluation of vegetation cover and land-surface albedo in MPI-ESM CMIP5 simulations,” *J. Adv. Model. Earth Syst.*, vol. 5, no. 1, pp. 48–57, 2013.

[60] K. Block and T. Mauritsen, “Forcing and feedback in the MPI-ESM-LR coupled model under abruptly quadrupled CO $_2$,” *J. Adv. Model. Earth Syst.*, vol. 5, no. 4, pp. 676–691, 2013.

[61] S. Hagemann, A. Loew, and A. Andersson, “Combined evaluation of MPI-ESM land surface water and energy fluxes,” *J. Adv. Model. Earth Syst.*, vol. 5, no. 2, pp. 259–286, 2013.

[62] C. J. Willmott, “On the Evaluation of Model Performance in Physical Geography,” *Spat. Stat. Model.*, no. 1967, pp. 443–460, 1984.

[63] E. Gregow, A. Pessi, A. Mäkelä, and E. Saltikoff, “Improving the precipitation accumulation analysis using lightning measurements and different integration periods,” *Hydrol. Earth Syst. Sci.*, vol. 21, no. 1, pp. 267–279, 2017.

[64] E. Gregow, E. Saltikoff, S. Albers, and H. Hohti, “Precipitation accumulation analysis - Assimilation of radar-gauge measurements and validation of different methods,” *Hydrol. Earth Syst. Sci.*, vol. 17, no. 10, pp. 4109–4120, 2013.

[65] C. C. Lundy, R. L. Brown, E. E. Adams, K. W. Birkeland, and M. Lehning, “A statistical validation of the snowpack model in a Montana climate,” *Cold Reg. Sci. Technol.*, vol. 33, no. 2–3, pp. 237–246, 2001.

[66] T. Chai and R. R. Draxler, “Root mean square error (RMSE) or mean absolute error (MAE)? -Arguments against avoiding RMSE in the literature,” *Geosci. Model Dev.*, vol. 7, no. 3, pp. 1247–1250, 2014.

ADDENDUM I

Table 6: Calculated statistics for model validation at all seven stations

		Kigali	r	R^2	RMSE	Index(d)	MBE	AME
Annual	RCP4.5		-0.66	0.43	226.34	0.99	4.96	4.96
	RCP8.5		-0.54	0.29	239.84	0.98	41.25	41.25
MAM	RCP4.5		-0.44	0.19	132.48	0.96	-8.15	8.15
	RCP8.5		-0.24	0.06	147.87	0.96	34.41	34.41
OND	RCP4.5		0.24	0.06	73.24	0.99	37.91	37.91
	RCP8.5		0.26	0.07	66.52	0.99	29.34	29.34

		Kamembe	r	R^2	RMSE	Index(d)	MBE	AME
Annual	RCP4.5		-0.02	0.004	201.86	0.99	-12.79	12.79
	RCP8.5		-0.02	0.004	211.86	0.99	11.86	11.86
MAM	RCP4.5		0.29	0.08	99.88	0.99	23.23	23.23
	RCP8.5		0.29	0.08	102.81	0.99	27.56	27.56
OND	RCP4.5		0.35	0.12	96.50	0.99	18.06	18.06
	RCP8.5		0.35	0.12	104.03	0.99	29.69	29.69

		Gicumbi	r	R^2	RMSE	Index(d)	MBE	AME
Annual	RCP4.5		0.04	0.00	273.20	0.99	-92.39	92.39
	RCP8.5		0.05	0.00	276.18	0.99	-98.30	98.30
MAM	RCP4.5		0.16	0.03	180.96	0.96	-124.18	124.18
	RCP8.5		0.16	0.03	180.95	0.96	-124.25	124.25
OND	RCP4.5		0.40	0.16	128.06	0.97	-1.97	1.97
	RCP8.5		0.40	0.16	127.91	0.97	-9.97	9.97
Annual	RCP4.5	Ngoma	-0.426	0.182	196.645	0.988	-5.002	5.002
	RCP8.5		-0.418	0.175	194.736	0.988	3.377	3.377
MAM	RCP4.5		-0.190	0.036	116.294	0.971	-23.457	23.457
	RCP8.5		-0.201	0.041	115.331	0.972	-19.651	19.651
OND	RCP4.5		0.042	0.002	78.929	0.982	12.618	12.618
	RCP8.5		0.040	0.002	78.419	0.982	14.179	14.179

		Rubavu	r	R^2	RMSE	Index(d)	MBE	AME
Annual	RCP4.5		-0.173	0.030	404.034	0.974	280.764	280.764
	RCP8.5		-0.172	0.030	402.903	0.974	279.650	279.650
MAM	RCP4.5		-0.083	0.007	181.548	0.954	93.004	93.004
	RCP8.5		-0.075	0.006	176.684	0.956	89.730	89.730
OND	RCP4.5		0.108	0.012	174.547	0.949	124.433	124.433
	RCP8.5		0.107	0.011	169.993	0.950	118.817	118.817

		Nyamagabe	r	R^2	RMSE	Index(d)	MBA	AME
Annual	RCP4.5		0.16	0.02	290.6	0.98	-36.09	36.09
	RCP8.5		0.14	0.02	292.2	0.98	-27.94	27.94
MAM	RCP4.5		0.22	0.05	156.9	0.97	-33.62	33.62
	RCP8.5		0.21	0.04	158.1	0.97	-25.19	25.19
OND	RCP4.5		-0.01	0.00	98.54	0.98	41.38	41.38
	RCP8.5		-0.03	0.00	99.49	0.98	41.51	41.51

		Nyagatare	r	R^2	RMSE	Index(d)	MBA	AME
Annual	RCP4.5		-0.43	0.18	185.5	0.99	59.6	59.6
	RCP8.5		-0.26	0.07	186.9	0.99	65.0	65.0
MAM	RCP4.5		-0.24	0.06	128.4	0.96	21.5	21.5
	RCP8.5		-0.24	0.06	128.6	0.96	23.4	23.4
OND	RCP4.5		-0.13	0.02	80.7	0.98	38.2	38.2
	RCP8.5		-0.13	0.02	82.1	0.98	40.2	40.2

ADDENDUM II

Table 7: Projected rainfall changes in the first decade (2021-2030)

Station	Scenario	2021-2030 DECADAL RAINFALL CHANGES		
		ANNUAL(mm)	MAM(mm)	OND(mm)
KIGALI	RCP 4.5	61.3	4.69	52.29
	RCP 8.5	63.45	29.4	32.32
KAMEMBE	RCP 4.5	49.48	-13.09	59.52
	RCP 8.5	55.1	-12.93	113.7
GICUMBI	RCP 4.5	-103.08	-159.9	-20.8
	RCP 8.5	-112.26	-160.5	-30.2
NGOMA	RCP 4.5	13.83	-33.83	19.89
	RCP 8.5	28.9	-27.43	20.93
RUBAVU	RCP 4.5	118.18	32.48	78.2
	RCP 8.5	115.31	38.35	72.3
NYAMAGABE	RCP 4.5	-57.4	-43.9	40.1
	RCP 8.5	-45.1	-37.3	39.9
NYAGATARE	RCP 4.5	88.1	30.7	41.6
	RCP 8.5	94.6	34.6	46.3

Table 8: Projected rainfall changes in the second decade (2031-2040)

Station	Scenario	2031-2040 DECADAL RAINFALL CHANGES		
		ANNUAL(mm)	**MAM(mm)**	**OND(mm)**
KIGALI	RCP 4.5	53.47	-16.66	50.28
	RCP 8.5	36.32	24.51	44.09
KAMEMBE	RCP 4.5	50.89	-11.76	75.9
	RCP 8.5	56.02	-10.87	104.9
GICUMBI	RCP 4.5	-104.81	-159.9	-18.7
	RCP 8.5	-111.62	-161.7	-24.9
NGOMA	RCP 4.5	20.42	-36.2	19.34
	RCP 8.5	18.04	-30.02	21.72
RUBAVU	RCP 4.5	130.65	31.61	77.33
	RCP 8.5	125.58	39.98	65.02
NYAMAGABE	RCP 4.5	-58.4	-38.6	40.1
	RCP 8.5	-43.3	-33.4	39.8
NYAGATARE	RCP 4.5	88.3	26.1	42.0
	RCP 8.5	93.5	29.5	43.0

Table 9: Projected rainfall changes in the third decade (2041-2050)

Station	Scenario	2041-2050 DECADAL RAINFALL CHANGES		
		ANNUAL(mm)	MAM(mm)	OND(mm)
KIGALI	RCP 4.5	62.47	19.12	43.43
	RCP 8.5	134.85	46.1	26.71
KAMEMBE	RCP 4.5	55.8	-21.1	81.75
	RCP 8.5	58.85	-11.32	100.27
GICUMBI	RCP 4.5	-102.6	-163.8	-22.3
	RCP 8.5	-115.7	-162.2	-38.2
NGOMA	RCP 4.5	26.91	-26.81	19.13
	RCP 8.5	47.26	-22.52	20.47
RUBAVU	RCP 4.5	126.55	35.06	72.7
	RCP 8.5	124.81	38.33	61.4
NYAMAGABE	RCP 4.5	-54.9	-48.3	40.2
	RCP 8.5	-47.6	-29.5	40.9
NYAGATARE	RCP 4.5	89.2	38.2	44.3
	RCP 8.5	95.8	37.5	48.5

Table 10: Projected climatology rainfall changes (2021-2050)

Station	Scenario	2021-2050 CLIMATOLOGY RAINFALL CHANGES		
		ANNUAL(mm)	MAM(mm)	OND(mm)
KIGALI	RCP 4.5	59.08	2.382	48.67
	RCP 8.5	78.21	33.34	34.37
KAMEMBE	RCP 4.5	52.06	-15.32	72.39
	RCP 8.5	56.66	-11.71	106.29
GICUMBI	RCP 4.5	-103.49	-161.2	-20.6
	RCP 8.5	-113.21	-161.4	-31.1
NGOMA	RCP 4.5	20.38	-32.28	19.45
	RCP 8.5	31.4	-26.66	21.04
RUBAVU	RCP 4.5	125.13	43.05	76.09
	RCP 8.5	121.9	48.88	66.25
NYAMAGABE	RCP 4.5	-56.9	-43.6	40.2
	RCP 8.5	-45.3	-33.4	40.2
NYAGATARE	RCP 4.5	88.5	31.7	42.6
	RCP 8.5	94.6	33.9	46