EVALUATION OF A REGIONAL CLIMATE MODEL FOR MAXIMUM AND MINIMUM TEMPERATURE IN RWANDA UNDER CLIMATE CHANGE.

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EVALUATION OF A REGIONAL CLIMATE MODEL FOR MAXIMUM AND MINIMUM TEMPERATURE IN RWANDA UNDER CLIMATE CHANGE.

BY

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A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF
MASTER OF SCIENCE IN ATMOSPHERIC AND CLIMATE SCIENCE

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Supervisor: **Prof. Bonfils Safari**

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DECLARATION

I declare that this dissertation is my original work and has not been submitted elsewhere for examination, award of degree or publications. For other people's work used, has specifically been acknowledged and referenced according to the University of Rwanda requirements.

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218015282

Signed………………………………………..

Date……………………………………………..

DEDICATION

This dissertation is dedicated to my wife KABANYANA Harriet, my daughters AKAZUBA Shine Sheila, AKANYANA Soleil Chania, AKIWACU Bernice Daniella and my late parents, brother and sisters.

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I am indebted to Almighty God for providing me with the strength to complete this course at the University of Rwanda.

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Last but not least, I would want to express my heartfelt gratitude to all of my classmates for their important contributions and constructive criticism, which helped to improve the study's outcome.

ABSTRACT

The aim of this research is to evaluate the ability of a Regional Climate Model (RegCM 4.7) used in the Coordinated Regional Climate Downscaling Experiment (CORDEX) to reproduce the seasonal mean maximum temperature (TX) and mean minimum temperature (TN) patterns over Rwanda during March, April, May (MAM) and October, November, December (OND) seasons.

The Regional Climate Model (RCM) outputs were evaluated using observational gridded datasets collected from the Rwanda Meteorology Agency between 1983 and 2005 period. All simulations performed are at a resolution of 25 km (0.22^o x 0.22^o) over the project domain. The analysis is based on determining how effectively the Regional Climate Model reproduces climatological trends and inter-annual variability in minimum and maximum temperatures.

We compared forecasts of Minimum and Maximum temperature changes by 2021 to 2050 and 2051 to 2080 for one Regional Climate Model using two Representative Concentration Pathways, RCP 2.6 and RCP 8.5 to assess uncertainty in these variables. The Bias, Root Mean Square Error, and trend analysis were used as statistical metrics of model performance. The findings from this study show that a Regional Climate Model (RegCM 4.7) reproduced inter-annual variability and trends in both minimum and maximum temperatures.

In general, for both March to May (MAM) and October to December (OND) seasons, the Biases and Root Mean Square Error (RMSE) resulting from the Regional Climate Model and driving General Climate Model in simulating Minimum temperature and maximum temperature are relatively small. Therefore the model can be used to simulate the future climate of Rwanda.

The results from projected minimum temperature (TN) and maximum temperature (TX) for March to May and October to December seasons using both Representative Concentration Pathways, RCP 2.6 and RCP 8.5 showed that minimum and maximum temperatures will generally increase for both seasons and Representative Concentration Pathways (RCPs), with an emphasis on the eastern region of the country.

The results from projected change for minimum temperature (TN) and maximum temperature (TX) during the March to May and October to December wet seasons using both Representative

Concentration Pathways, RCP 2.6 and RCP 8.5 showed a positive change (warming) for minimum temperature and maximum temperature almost everywhere in the country, however the change in March to May is higher compared to the change in October to December. For most locations, average changes in minimum temperature were greater than associated changes in maximum temperature for both MAM and OND across the two RCPs.

Results from trends show the highest trend of 0.04757^{o}C/year for maximum temperature during March to May (MAM) season with RCP 8.5 scenario and the lowest trend of -0.0006^{o}C/year for maximum temperature is observed during MAM with RCP 2.6. Similarly, Results show the highest trend of 0.0429^{o}C/year for minimum temperature during MAM with RCP 8.5 scenario and the lowest trend of 0.0005^{o}C/year for maximum temperature is observed during October to December with RCP 2.6.

KEY WORDS

Regional Climate Model, maximum temperature, minimum temperature, Climate change.

LIST OF SYMBOLS AND ACRONYMS

RCM: Regional Climate Model

GCM: Global Climate Model

IPCC: Intergovernmental Panel on Climate Change

CORDEX: Coordinated Regional Climate Downscaling Experiment

TN: Minimum Temperature

TX: Maximum Temperature

TA: Average Temperature

MAM: March to May

OND: October to December

NCEP: National Centres for Environmental Prediction

RCPs: Representative Concentration Pathways

WRF: Weather Research and Forecasting

CRU: Climate Research Unity

GHG: Greenhouse Gases

AR5: The fifth assessment report of the Intergovernmental Panel on Climate Change

SRES: Special Report on Emissions Scenarios

RMSE: Root Mean Square Error

IRI: International Research Institute for Climate and Society.

ENACTS: Enhancing National Climate Services

WRSI: Water Requirement Satisfaction Index

IIASA: International Institute for Applied Systems Analysis

ESGF: Earth System Grid Federation

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CHAPTER ONE: INTRODUCTION

1.1. Background

Rwanda’s population is approximately 12,000,000 with 416 people per square kilometer as population density. Rwanda is one among other countries in Africa with the highest population density, with a growth rate of 2.8% per year as reported by Safari (2012) and more than 90% of the Rwandan population use wood and charcoal as source of energy. The expanding population together with urban intensification as well as the effect of climate changes have influenced Rwanda’s socio-economic by causing pressure on land, water, food and energy resources. The same report showed that the analysis of temperature on annual time scale has indicated an abrupt change of temperature indicating that the climate of Rwanda was really changing.

According to Ngarukiyimana et al. (2021), temperature is one of the most important climate parameters that has a considerable impact on human, agricultural, and thermal comfort. Climate change, according to Nzeyimana and Kwitonda (2014), has caused Rwanda to experience periodic droughts and poor rainfall like never before which affected Rwanda's dual aims of food security and poverty alleviation. The same report indicated that Eastern Rwanda is the most vulnerable drought prone area, according to the WRSI for maize (a proxy indicator for drought prone areas). Figure 1.1 depicts Rwanda's disaster-prone locations, with Kayonza, Nyagatare as well as Kirehe being the most drought-prone.

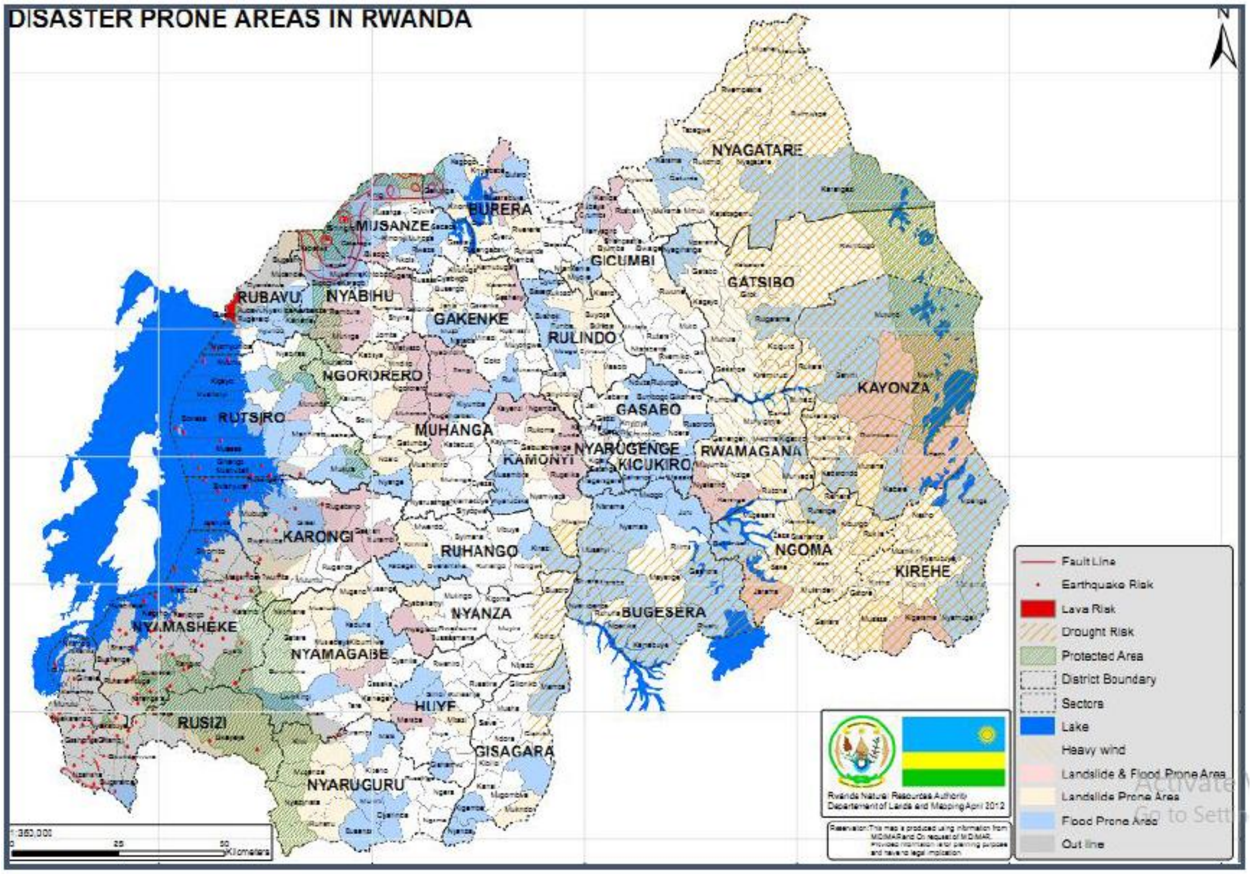

Figure 1. 1: Extent of drought affected areas of Rwanda (MINAGRI, 2014).

According to Muhire et al. (2015), Temperature rises of 0.18 °C to 0.6 °C per decade were observed not only in Rwanda between 1961 and 1990 but also in other African countries such as South and North Sudan, Ethiopia, and Uganda between 1961 and 2000. The same report showed that between 1961 and 2000, an annual mean temperature increase of 0.1 °C to 0.3 °C per decade was observed in Burundi, interior Kenya and Tanzania, Madagascar, Eritrea, and South Africa.

Barreca et al. (2016); Heal & Park (2016); Githeko et al. (2006) reported that unusually high maximum temperatures are positively associated with many malaria cases. Therefore, a study of expected temperatures at the regional level is required to improve readiness. This study, which aimed to evaluate a Regional Climate Model to simulate minimum (TN) and Maximum (TX) temperatures over Rwanda from 2021 to 2050, and 2051 to 2080 was undertaken for this reason.

1.2. Problem Statement

The current variations in temperature and rainfall patterns have been related to increased greenhouse gas concentrations due to fossil fuel consumption, increased deforestation, and anthropogenic activities. Temperature and precipitation variations on global, regional, and local scales are of relevance because of their impact on ecosystems, according to Houghton et al. (1995) and Li et al. (2019). Warming in minimum and maximum temperatures has been observed globally, and it is widely agreed that maximum and minimum temperature trends and variability are critical in detecting climate change implications on human health (Ngarukiyimana et al., 2021). The Intergovernmental Panel on Climate Change (IPCC) estimated a 0.72°C increase in global temperature from 1951 to 2012 in its fifth assessment report (AR5). Eriksen & oBrien (2008) reported a temperature increase of about 0.7 to 0.9°C across Rwanda in the last century.

As reported by Mugunga (2019), the availability of water, food, energy and other socio-economic needs in Rwanda is influenced by daily weather, monthly, seasonal and inter-annual climate variability. Maximum and minimum temperatures are the most significant weather parameters that impacts socio-economic activities over the country of Rwanda. It is now widely admitted that climate change impacts on minimum and maximum temperatures are occurring and are expected to amplify in the future. Kim *et al.*, (2014) reported that the impacts are highly uncertain and usually scientists and decision makers prefer to have a quantitative assessment of these associated uncertainties. However, there is a big gap on the understanding of uncertainties from projected temperatures by high resolution Regional Climate Models in Rwanda due to insufficient studies on related subject which is a key challenge for adaptation planning. Thus the evaluation of a High Resolution Regional Climate Model for Maximum and Minimum Temperature in Rwanda under Climate Change is highly needed.

1.3. Objectives

The goal of this dissertation is to evaluate a Regional Climate Model for Maximum and Minimum temperature in Rwanda under Climate Change.

The specific objectives are:

- ✓ To assess the performance of RegCM 4.7 CORDEX model to simulate maximum and minimum temperature over Rwanda during MAM and OND from 1983-2005;
- ✓ To determine the projected maximum and minimum temperatures over Rwanda during MAM and OND from 2021-2050 and from 2051-2080.
- ✓ To determine the trend of historical and projected average temperature over Rwanda during MAM and OND.

1.4. Hypothesis of the Study

Evaluation of a Regional Climate Model will show its ability to simulate observed maximum and minimum temperature in Rwanda under climate change.

1.5. Justification of the problem

Climate change as well as climate variability are threats to farmers as animal production and crop depend on climatological parameters include rainfall and temperature (Adnew Degefu et al., 2018). Therefore, regional climate models are becoming more essential as a source of information regarding potential climate change implications (Challinor et al., 2007).

However, in order to make informed adaptation decisions, the uncertainties associated with their outputs must be acknowledged and considered. Very few research studies on Regional Climate Models evaluation under climate change of Rwanda have been carried out and most of them were done on rainfall, this work is expected to fill in the gaps through increasing the knowledge on the evaluation of regional climate models performance for maximum and minimum temperatures of Rwanda under Climate Change. The findings will be used to guide future planning and decision-making in areas such as agriculture, energy development, and disease control.

Thus, it is critical to have a thorough understanding of historical maximum and minimum temperatures fluctuation in order to mitigate the impact of future changes. Furthermore, no comprehensive research made in Rwanda to assess the regional climate models in TX and TN over the entire country which is the particularity of this work.

1.6. Study area and its climatology

1.6.1 Study area

The Study area is Rwanda (Fig 1.2) which is a country in East-central Africa with area of 26,338 square kilometers on the eastern shoulder of the Kivu-Tanganyika rift, situated between 1˚41' and 2˚51" south latitude, 28˚53" and 30˚53" east longitude as reported by Safari (2012). Rwanda is bordered by Tanzania (East), Democratic Republic of Congo (West), Uganda (North) and Burundi (South). It has complex spatiotemporal natures of daily, monthly and seasonal weather due to the topography and water bodies distribution influences (Uwimbabazi et al., 2022).

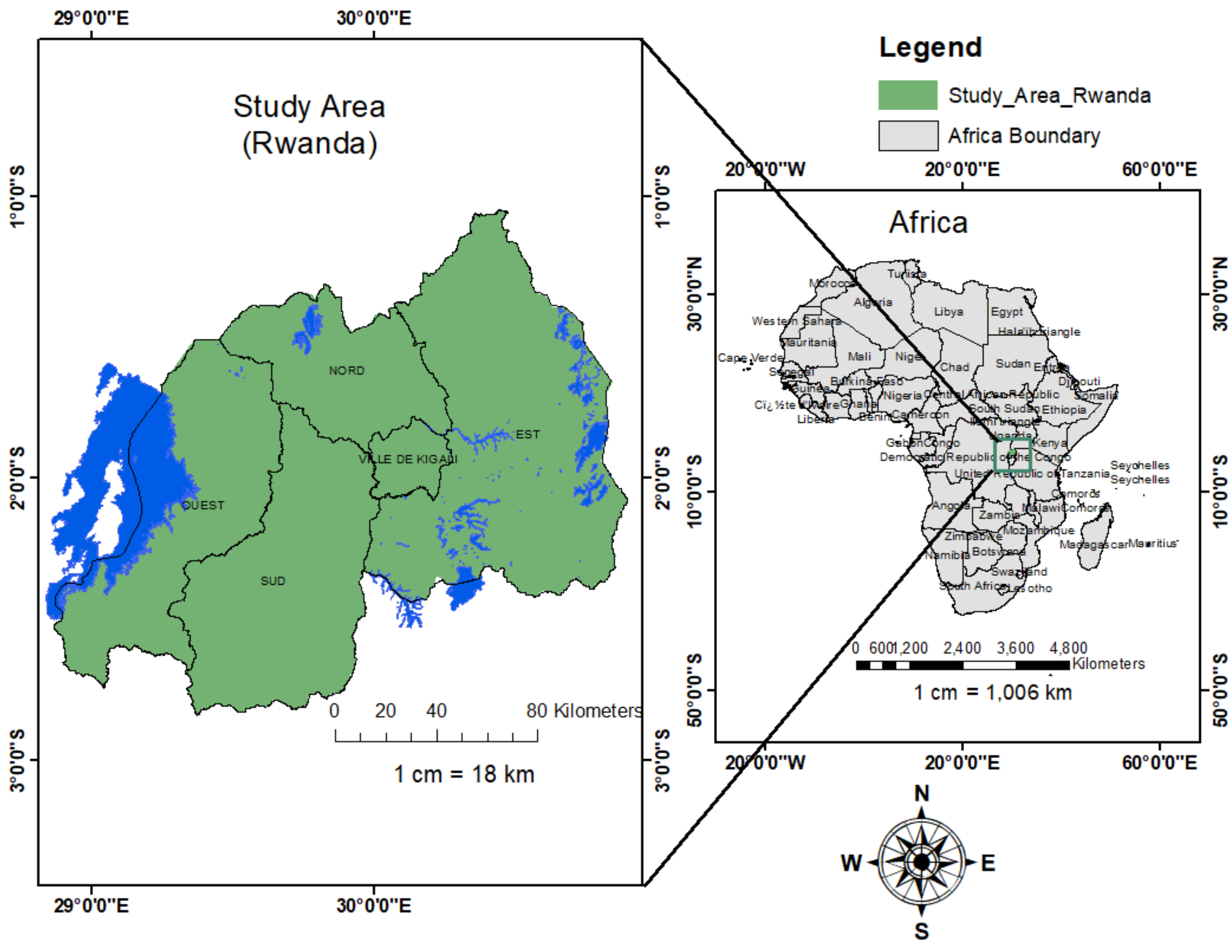

Figure 1. 2: map of the Study area (generated by ArcGIS).

1.6.2 Climatology of Rwanda

As reported by Mukhala, Ngaina and Maingi (2017) East Africa has a diverse climate and topography, ranging from humid tropical lowlands to high and arid highland plateaus. Rwanda specifically has a pleasing moderate and tropical climate due to its high altitude. Rwanda's temperature fluctuates throughout the year, with two maximums and two minimums.

The same report indicate that, the lowest maximum temperature is recorded in February, while the highest maximum temperature is recorded in August. The two minima occur in June and November, respectively. Rwanda's average temperature is roughly 20°C and fluctuates depending on the topography. The warmest annual average temperatures are found at the eastern plateau (20°C - 21°C) and Rusizi's south-eastern valley (23°C - 24°C), while the coolest are found at central plateau (17.5°C - 19°C) and highlands (<17°C).

Precipitation regimes in Rwanda are bimodal, resulting in two wet seasons per year. The long rainy season (MAM) is locally known as Itumba, while the shot rainy season (OND) is locally known as Umuhindo and both depend on the ITCZ movement (Safari, 2012) . The main factors that influence climatology of Rwanda are: Congo Air mass, Inter-Tropical Convergence Zone (ITCZ), Tropical Cyclones, local systems, Global Tele-connections and Sub-tropical Anticyclones as reported by Mugunga (2019); Safari (2012).

CHAPTER TWO: LITERATURE REVIEW

2.1. Climate change modeling

With the confirmation of continuous climate change, analyzing its influence on regionally important sectors has become a key concern, particularly for policymakers developing action plans to prevent and adapt to future climate change consequences as reported by IPCC (2001).

In the study conducted by Jones et al. (2004), Climate modeling is simulating the interactions of climate system components and their responses to solar radiation between the top of the atmosphere and the Earth's surface using computer models of the climate system and defined it as a mathematical representation of the climate system expressed as computer codes that can be run on a powerful computer to provide a quantitative and comprehensive description of how atmospheric pressure, temperature, clouds, precipitation and water vapor respond to solar heating of the atmosphere.

Harries et al. (2001) study showed that forecasts of mean atmospheric temperature and precipitation for the twenty-first century imply that ecological, economic, and social disruptions are likely in the future. Refer on all the above mentioned reports, Rwanda is not isolated. Though the evaluation of a regional climate model in Mean and Extreme Maximum, Minimum Temperature under Climate Change of Rwanda is needed.

2.2. Climate projection

Global circulation models (GCMs) are used to forecast future temperatures and precipitation, according to Boko et al. (2007), and as reported in the study of Giorgi et al. (2009), it is designed to replicate the earth's climate over the entire world, but due to its coarse spatial resolution, it has limitations when it comes to portraying local nuances of climate features. Global models are unable to accurately describe extreme occurrences in terms of the regional and local implications of climate variability and change due to their coarse resolution. Climate model evaluation is a critical step in determining the uncertainty in future climate projections, according to Nature (2010), Kim and Lee (2003), and Hong et al. (2010) studies.

Among the most important users of climate information are policymakers, who rely on forecasts of climate change implications in their decision-making according to Kim *et al.* (2014). Therefore, climate downscaling from coarse resolution GCMs to regionnal scale is required for the computation of local features and to get the relevant temporal and spatial scales for climate change studies.

Endris et al. (2013) and Gbobaniyi et al. (2014) reports showed that RCMs dynamically downscale GCM output to scales more suited to end-users, making them a useful tool for understanding local climates in areas with complex topography and accounting for land surface heterogeneity. Krishnamurti et al. (2000); Mearns et al. (2009); Giorgi et al., (2007) reported that Model evaluations are usually carried out by comparing model outputs to reference data derived from observations, using appropriate metrics.

IPCC 1995, 2001, 2007; Bader et al. (2008); Meehl et al. (2007) developed a foundation for GCM evaluations but RCM evaluation is still in its infancy when it comes to collective and systematic evaluation as reported by Nikulin et al. (2012); Mearns et al. (2012); Tapiador (2010)**.** Also the RCM simulations in the Coordinated Regional Climate Downscaling Experiment were analyzed by Giorgi et al. (2009); Jones et al. (2011). Boko et al. (2007) showed that the region of Africa is vulnerable to climate change and has become the region of special concern in the CORDEX program.

In Kim et al. (2013) study, Regional climate simulations of Europe are shown for air temperature and extreme events of heat and cold waves during a 60-year period (1950–2010) using a 25 km resolution WRF model with NCEP 2.5 degree analysis for initial/boundary conditions. When forced by global climate models (GCMs), RCMs have been proven to sometimes produce significant biases in the mean climate as reported by Jacob et al. (2007) and even more, so in terms of extreme conditions Jones et al. (2004) found that in the tails of temperature probability distributions, there is a far wider gap across RCMs than in simulated averages, both in today's climate and in simulated climate change signals.

As reported in the study of Giorgi et al. (2009), CORDEX chose Africa as one of its target areas for three primary reasons. Climate variability, relatively low adaptive ability of its economies and important changes of temperature and precipitation patterns contributes to the region's high susceptibility for different sectors.

Different research have been conducted to evaluate the performance of climate model outputs in relation to CORDEX simulations across Africa. The study by Luhunga, Botai and Kahimba (2016) evaluated CORDEX RCMs in modeling TX and TN over Tanzania using historical station data and they discovered that RCMs operate differently a wide region of Tanzania. Similarly, Mutayoba and Kashaigili (2017) assessed CORDEX performance at the catchment level to see how well the various RCMs in CORDEX, as well as the ensemble average of the RCMs, reproduce annual cycles, inter-annual variability, and rainfall trends. They found that the ensemble mean predicted rainfall magnitude and trends better than individual model findings.

The study by Akinsanola et al. (2015) and Akinsanola and Ogunjobi (2017) indicated that Some of the RCMs in West Africa also exhibited a considerable bias of individual models depending on sub region and seasons.

Several studies related to RCMs have been carried out in Rwanda include the studies of Mugunga (2019); Muhire et al. (2015); Mukhala et al. (2017); Ntwali et al. (2016) and Umuhoza et al. (2021). The majority of the studies focused on the performance of multimodal numerical simulations and multi-observational data bases, with seasonal cycles and spatial variations of precipitation in Rwanda. Most of them employed globally available gridded data sets and satellite based data sets as a reference to evaluate the CORDEX-Africa RCMs output.

Furthermore, some of these studies used a single parameter to describe the overall performance of the model. In all regions, not all RCMs are found to be equally essential. For example recent study by Umuhoza et al. (2021) showed that the RCM's rainfall simulation varies by region, doing well in some and poorly in others and Ntwali et al. (2016) found that RCM estimation is sensitive to elevation at higher elevation. The inconsistency of performance across regions and seasons found in the works above mentioned highlights the necessity to assess the sensitivity of regions to RCM selection. The RCMs' performance could be evaluated properly to achieve this.

This study was initiated to evaluate the performance of one RCM from CORDEX RCMs driven by NCC-NorESM1-M GCM based on RCP2.6 and 8.5 scenarios in simulating the seasonal mean, minimum and maximum temperature over Rwanda. In this study MAM and OND long and short rain seasons respectively were chosen to see the interconnection between rain seasons and associated temperature and how RCMs perform in two different seasons.

2.3. Climate Change Scenarios

According to IPCC, Climate scenarios, are probable projections of the future. Future greenhouse gas (GHG) emissions and concentrations are highly uncertain and depend on future developments include future population growth, economic growth, energy use, uptake of renewable energy, technological change, deforestation and land use. The climate modelling community has developed four Representative Concentration Pathways (RCPs).

The four RCPs are alternative images of how the future might unfold and are an appropriate tool with which to analyse how driving forces may influence future emission outcomes and to assess the associated uncertainties. RCPs are space and time dependent trajectories of future greenhouse gas concentrations and different pollutants caused by different human activities. They assist in climate change analysis, including climate modeling and the assessment of impacts, adaptation, and mitigation.

They also assists policymakers in determining effective policy responses to the change (IPCC-SAR, 1995). According to van Vuuren et al. (2011), four RCP emissions scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5 were published for use in climate change studies. The naming convention reflects socioeconomic pathways that reach a specific radiative forcing by the year 2100.

In the present study, RCP2.6 and RCP8.5 were used for both TN and TX projections (table 2).
According to Van Vuuren et al. (2007a), RCP2.6 is a “peak-and-decline” scenario; its radiative forcing level first reaches a value of around 3.1 W/m^2 by mid-century, and

returns to 2.6 W/m^2 by 2100. In order to reach such radiative forcing levels, greenhouse gas emissions are reduced substantially, over time. The emission pathway is representative of scenarios in the literature that lead to very low greenhouse gas concentration levels.

As reported by Riahi et al. (2007), RCP 8.5 is a typical 'business-as-usual' scenario. It is characterized by a rising radiative forcing pathway that reaches 8.5 W/m^2 by 2100, before increasing to 12 W/m^2 by 2250. Different reports such as Rogelj et al. (2011) and Riahi et al. (2011) showed that GHG emissions in the RCP8.5 continue to rise as a result of the high fossil intensity of the energy sector, rising population and concomitant high food demand.

CHAPTER THREE: DATA AND METHODOLOGY

This section is reserved to the discussion of the data and model used in the present study and different methodologies used to accomplish the aims of the study.

3.1. Data Sources

This section presents climatological data used in this study included observed temperature and simulated data.

3.1.1. Observed climate data

Historical data for seasonal mean TN and TX for the period 1983-2005 used in this study were obtained from Rwanda Meteorology Agency, made in help with IRI namely ENACTs data set and covers the whole country (Siebert et al., 2019).

3.1.2. Simulated climate data

In the present work, simulated data used include TX and TN are obtained from CORDEX-core available at ESGF (Earth System Grid Federation) portal. Remedio et al. (2019) and Nikulin et al. (2012) provide thorough information on the CORDEX models, including model dynamics, physical parameterisation, as well as lateral and boundary conditions, among other things. Furthermore, throughout the period 1951-2100, the output runs in transient mode. The RegCM 4.7 RCM CORDEX model driven by NCC-NorESM1-M GCM is analysed based on RCP2.6 and 8.5 scenarios. All simulations are run at a resolution of 25 km (0.22^{o} x 0.22^{o}) over the scope of the project. The higher resolution of the RCM play a role in the improved reproduction of maximum and minimum temperatures signal for complex topography of the country.

3.2. Data limitations

In general, the EAC region, and Rwanda in particular, lacks high-quality observation datasets with the temporal and spatial precision required to evaluate RCM models. Therefore, the climate change modeling was based on data that had been post-processed and was available through the CORDEX data portal. Endris *et al.* (2013) published a paper detailing the limits of CORDEX models in the Africa region.

3.3. Methodology

3.3.1. Downscaling of CORDEX regional climate model

Dynamical downscaling approaches were applied in this work, in which downscaled climate change models took data from GCMs and interpreted them in terms of local climatic dynamics. To model regional climate, dynamical downscaling uses an RCM that is driven by a GCM. The RCMs' key advantage is their capacity to explicitly predict atmospheric processes and land cover changes, quoted from Murphy (1999) and Ogwang et al. (2016).

3.3.2. Assessment of the skill of CORDEX Regional Climate model to simulate the climate of Rwanda

This section presents different methods used to assess the performance of the RegCM 4.7 model to simulate seasonal mean and extreme temperature over Rwanda.

In the present study the framework of model evaluation by Murphy and Winkler (1987) is followed. According to Omondi (2015) Graphical and error analysis techniques were used to determine the climate model's capacity to match long-term historical climate observations. In this study BIAS, and RMSE Error analysis techniques are used to validate the model performance against observations. Techniques were also used by Dasari et al. (2014).

$$BIAS = \frac{1}{n}\sum_{i=1}^{n}(T_i - \bar{O}) \qquad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(T_i - O_i)^2}{n}} \qquad (2)$$

Where O_i is an observed variable, T_i is a modeled variable, $\bar{O}$ represents average over all the data and “n”is the total number of locations that predicted data are compared against observations.

For a continuous variable, bias is a measure of mean error as reported by Legates et al. (1999) and according to Luhunga et al. (2016) report, The Bias is a percentage value that indicates whether RCMs underestimate or overestimate a specific climate variable. Positive Bias values suggest climate model overestimation, whereas negative values imply climate model underestimate. The RMSE is a measure of how good a model is, and the smaller it is, the better it is.

3.3.3. Minimum and maximum temperature projection

To achieve the second specific objective which is to determine the projected maximum and minimum temperatures over Rwanda during rainy season from 2021-2050 and from 2051-2080, the RegCM 4.7 CORDEX model driven by NCC-NorESM1-M GCM was used, it is randomly chosen from other CORDEX models due to the limited time of this study and budget limitations. All simulations performed are at 25 km (0.22º x 0.22º) resolution over the project domain based on RCP2.6 and 8.5 scenarios.

The RCMs simulate different climate variables such as TN and TX at each grid point. The quality of their output can be evaluated against actual measurements from weather stations using several techniques. One of the methods is to interpolate gridded climate variables to the location of weather stations and compare the results with observed station data (Spatial variability of minimum and maximum temperature) and temporal variability of projected TN and TX was investigated using a time series analysis.

3.3.4. Determination of trend of past and future climate over Rwanda

This activity involved determination of spatial and temporal variability of past and future climate over Rwanda. Statistical methods were used to test the statistical significance of the observed trends in a time series. A similar method has been used by Safari (2012). Mann-Kendall (MK) and Theil-SEN slope estimator methods are used to test the ability of the RegCM 4.7 driven by NCC - NorESM1-M GCM to simulate trends and the magnitude of the trends in inter-annual series of TN and TX. All trends are computed at station level for the period 2021–2080.

To perform a Mann-Kendall test, compute the difference between the later-measured value and all earlier-measured values, (y_j - y_i), where j>i, and assign the integer value of 1, 0, or –1 to positive differences, no differences, and negative differences, respectively. The test statistic, S, is then computed as the sum of the integers:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(y_j - y_i) \tag{3}$$

$$Sign(y_j - y_i) = \begin{cases} +1 \; if (y_j - y_i) > 0 \\ 0 \;\; if \; (y_j - y_i) = 0 \\ -1 \; if \; (y_j - y_i) < 0 \end{cases} \tag{4}$$

When S is a high positive number, later measured values are larger than earlier recorded values, indicating an upward tendency while a downward trend is indicated when S is a high negative number and later values are smaller than earlier values and when the absolute value of S is minimal, there is no indication of a trend as reported by Sen (1968). Theil-Sen slope estimator is calculated as follows:

$$\alpha = median \left(\frac{y_j - y_i}{x_j - x_i} \right) \tag{5}$$

The same method was used by Mukhala, Ngaina, and Maingi (2017) and Safari (2012).

CHAPTER FOUR: RESULTS AND DISCUSSION

This chapter covers the results that were obtained from various methods that were discussed in the previous chapter 3, which focuses on the study's objectives.

4.1. Assess the RegCM 4.7 model in MAM and OND for maximum and minimum temperature.

It is done by assessing the performance of RegCM 4.7 model during the rain seasons MAM and OND using TN and TX historical data from 1983 to 2005.

4.1.1. Performance of RegCM 4.7 model for maximum temperature during MAM and OND wet seasons.

Fig 4.1 show the spatial pattern of the seasonal mean maximum temperature (TX) simulated by RegCM 4.7 model and the observed seasonal mean maximum temperature for MAM and OND from 1983 to 2005. The model overestimate the maximum temperature compared to observed maximum temperature mainly in Eastern part of the country whereas the model reflect observation in western region of the country except at the boundaries of lake Kivu and small part of South west where the model underestimate the maximum temperature compared to observed during MAM and this is the same during OND.

4.1.2. Performance of RegCM 4.7 model for minimum temperature during MAM and OND wet seasons.

Fig 4.2 show the spatial pattern of the seasonal mean minimum temperature (TN) simulated by RegCM 4.7 model and the observed seasonal mean minimum temperature of MAM and OND from 1983 to 2005. The model overestimate little bit the minimum temperature compared to observed minimum temperature specifically in Eastern region of the country during MAM. During OND it is the same but overestimation is more reinforced specifically in north east and south east of the country.

4.2. Results of the skill of the Statistical Model

This section highlights the analysis from different methods used to assess model skill including Root Mean Square Error and Bias.

4.2.1. Results from RMSE and BIAS for TX and TN during MAM and OND seasons

Fig 4.3 and Fig 4.4 show the Bias and RMSE spatial pattern of the maximum temperature and minimum temperature respectively during MAM and OND. The smaller the RMSE and Bias the improved the fit test.

The outcomes of the model show cold Bias and very small values for RMSE during the two seasons (Fig 4.3), this identify the capability of the model to produce the observed maximum temperature. The outcomes of the model show overestimation of minimum temperature for Bias (warm Bias) and for RMSE during OND (Fig 4.4), especially in central part and South West of the country, this identify the weakness of the model to produce the observed minimum temperature during OND season. The outcomes of the model show very small values for RMSE during MAM, this identify the capability of the model to produce the observed minimum temperature during MAM season.

4.3. Results of the model verification using inter-annual variability of observed and model temperature during MAM and OND rain seasons.

As it is seen on the Fig.4.5 and Fig 4.6, the model is quiet well simulate the maximum observed temperature (TX) for both MAM and OND but the correlation is high in MAM while for minimum temperature (TN), the model overestimate the observed minimum temperature from 1989 to 1995 during MAM and from 1998 to 2003 during OND. In general the model reproduce the inter-annual variability for minimum temperature but the correlation is relatively lower than maximum temperature.

4.4. Minimum and maximum temperature projection

In this section, the projected minimum and maximum temperature during MAM and OND rain seasons was conducted based on the RegCM 4.7 model driven by NCC - NorESM1-M GCM, the RCP 2.6 and RCP 8.5 were used. The maps were produced by the spatial interpolation with help of kriging method, it is selected from other methods because it has greater potential to generate more accurate and validated surfaces compared to other types of spatial interpolation methods.

4.4.1. Projected maximum temperature during MAM and OND rain seasons

Projected maximum temperature (TX) and projected change from 2021 to 2050 and from 2051 to 2080 using RCP 2.6 and RCP 8.5 from RegCM 4.7 model during MAM and OND rain seasons in comparison with observed maximum temperature were presented on Fig 4.7.

During Mach to May (MAM) long rain season, the model indicated that the maximum temperature will increase in general everywhere in the country for two RCPs and for both period of projection except at near Lake Kivu in 2021 to 2050 based on RCP 2.6 where the model indicate the decrease of temperature (cool). The increasing of temperature (warming) appear to be important in the eastern part of the country.

The model (Fig 4.7) showed the positive change (warming) of maximum temperature almost everywhere in the country for both RCPs and both projection periods during MAM. The model indicated the negative change of -2-0^{o}C at the south west near lake Kivu, small part of north and south for 2021-2050 using RCP 2.6, the positive change of 4-6^{o}C was indicated over the whole country whereas the severe warming of 6-8^{o}C was indicated in south east and a small part of west in 2051 to 2080 using RCP 8.5. The positive change of 4-6^{o}C was also indicated in east West near lake Kivu for 2021-2050 using RCP 8.5 and the model showed the positive change of 0-2^{o}C over south west, central and the small part of north east region in 2021-2050 using RCP 8.5. In 2021-2050, the model showed the change of 0-2^{o}C over almost everywhere in the country based on RCP 2.6.

During October to December (OND) short rain season, the model (Fig 4.7) indicate that the temperature will increase more impotently in Western region, and a small part of South east of the country whereas the model indicate the decrease of temperature in the Central region, South and North east part of the country for both RCPs from 2021 to 2050 and 2051 to 2080.

The model (Fig 4.7) showed the important positive change (warming) of maximum temperature in western region and south east of the country for both RCPs in 2021 to 2050 and 2051 to 2080 during OND season. The model indicated the negative change of -2-0^{o}C at the south west near lake Kivu, big part of south, central and north east for 2021-2050 using both RCPs and in 2051 to 2080 using RCP 8.5, the positive change of 4-6^{o}C was indicated over the west in 2051 to 2080 using RCP 8.5. The positive change of 2-4^{o}C was indicated in west, north west and south east in 2021-2050 using both RCPs, and 2051 to 2080 using RCP 8.5. In 2051 to 2080, the model showed the change of 0-2^{o}C over almost everywhere in the country and cooling of -2-0^{o}C in north east based on RCP 8.5.

4.4.2. Projected minimum temperature during MAM and OND rain seasons

Fig 4.8 show projected minimum temperature (TN) and projected change from 2021 to 2050 and from 2051 to 2080 using RCP 2.6 and RCP 8.5 from RegCM 4.7 model during MAM and OND rain seasons in comparison with observed maximum temperature.

During Mach to May (MAM) long rain season, the model (Fig 4.8) indicated that the minimum temperature will increase in general over the whole country in 2021-2050 and in 2051-2080 based on RCP 2.6 and RCP 8.5. The increasing of minimum temperature (warming) appear to be important in the eastern part of the country for RCP 8.5.

In 2021 to 2050 as well as in 2051 to 2080, the model (Fig 4.8) showed the positive change (warming) of minimum temperature almost everywhere in the country for both RCPs during MAM. In 2051 to 2080, the model showed the positive change of 5-6^{o}C over the north east and west near Lake Kivu, whereas the 4-5^{o}C change was indicated in the rest parts of the country based on RCP 8.5. The positive change of 4-5^{o}C was also indicated in north east for 2021-2050 using both RCPs and in 2051-2080 using RCP 2.6. The lowest change of 0-2^{o}C was indicated over the south east in 2021-2050 and 2051-2080 based on RCP 2.6 during MAM.

During October to December (OND) short rain season, the model (Fig 4.8) indicated that the minimum temperature will increase generally everywhere in the country for both 2021-2050 and 2051-2080 periods using RCP 2.6 and RCP 8.5. The increasing of minimum temperature (warming) appear to be important in the eastern part of the country for 2021-2050 and 2051-2080 using RCP 8.5. The model (Fig 4.8) showed the highest change (warming) of 5-6^{o}C TN over south west region of the country in 2051 to 2080 using RCP 8.5 and in 2021 to 2050 over west region using RCP 2.6. The lowest change of -1-0^{o}C TN was indicated over North West and central part of the country in 2021-2050 using RCP 2.6 scenario.

4.5. Trend analysis

In this section trends of minimum and maximum temperatures based on RCP 2.6 and RCP 8.5 scenarios over 2021-2080 period were produced.

4.5.1. Trend of maximum temperature for RCP 2.6 and RCP 8.5 scenarios for the period 2021-2080.

Fig 4.9 and table 3 show that the trend is more significant during MAM for RCP 8.5 scenario (with α = 0.04757^{o}C/year) than OND with the same scenario (α = 0.0315^{o}C/year) whereas there is no significant trend with RCP 2.6 for both seasons. This can be justified by Riahi et al. (2011).

4.5.2. Trend of minimum temperature for RCP 2.6 and RCP 8.5 scenarios for the period 2021-2080.

Fig 4.10 and table 3 show that the trend is more significant during MAM for RCP 8.5 scenario (with α = 0.0429^{o}C/year) than OND with the same scenario (α = 0.0366^{o}C/year) whereas there is no significant trend with RCP 2.6 for both seasons.

Generally, the trend is high for RCP 8.5 during MAM for both TX and TN. During OND, the trend of minimum temperature is more significant (α = 0.0366^{o}C/year) than the trend of maximum temperature (α = 0.0315^{o}C/year) whereas during MAM the trend of maximum temperature is more significant (α = 0.0429^{o}C/year) than the trend of minimum temperature (α = 0.0429^{o}C/year). This can be justified by Van Vuuren et al. (2011).

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

In this study, one CORDEX regional climate model (RegCM 4.7) driven by one GCM (NCC - NorESM1-M) is analysed for its ability to simulate observed TN and TX over Rwanda. The analysis is based on determining how well the RCM reproduce climatological trends, and inter-annual variability of TN, and TX. Statistical measures of model performance that include the bias, root mean square error, and trend analysis were used. Results showed that RegCM 4.7 reproduced inter-annual variations and trends in TN as well as in TX. The biases and the Root Mean Square Error arising from the RCM and driving GCM in simulating TN and TX are relatively small for both MAM and OND. This show that the model simulate well the observed and the predicted temperature for both seasons therefore can be used for other seasonal predictions of temperature.

In agreement with Lobell et al. (2007); Muhire et al. (2015); Ngarukiyimana et al. (2021); Safari (2012), the results showed that the minimum and maximum temperature will generally increase for MAM and OND, increasing of temperature appear to be more significant in eastern region of the country. The model indicated the positive change (warming) for both TN and TX in the whole country, Osima et al. (2018) found similar results. In agreement with Lobell et al. (2007), average changes in TN across all RCPs were larger than associated changes in TX for both MAM and OND for most locations.

Results from trends show the highest trend of 0.04757^{o}C/year for TX during MAM with RCP 8.5 scenario and the lowest trend of -0.0006^{o}C/year for TX is observed during MAM with RCP 2.6.

Generally, the trends are high during MAM with RCP 8.5. This is most likely explained by the increasing emissions of greenhouse gases due to the demographic, economic trends, and the change of land use as reported by Riahi et al. (2011).

These findings are meaningful to policymakers due to the important projected changes of temperature that can be considered in their planning and furthermore for climate modelers, comparative studies are needed for further studies by using one RCM driven by different GCMs and different RCMs driven by different GCMs with diverse RCPs for constraining uncertainties.

ADDENDUM

ADDENDUM 1: TABLES

Table 1: presents description of RegCM 4.7 CORDEX model used in this study.

Domain	**Model (RCM)**	**Institution**	**Driven GCM**
AFR _22	RegCM4-7	(ICTP) The Abdus Salam International Centre for Theoretical Physics, (Italy).	NCC-NorESM1-M

Table 2: Representative Concentration Pathways (RCPs) as reported by Moss et al. (2010)

Name	**Radiative forcing**	**CO_2 Equiv (ppm)**	**Temp anomaly (°C)**	**Pathway**	**SRES temp anomaly equiv**
RCP 2.6	3 Wm^2 before 2100, declining to 2.6 Wm^2 by 2100	490	1.5	Peak and decline	None
RCP 8.5	8.5 Wm^2 in 2100	1370	4.9	Rising	SRES A1F1

Table 3: Trends of TN and TX for RCP 2.6 and RCP 8.5 scenarios and their significance level α for the period 2021-2080. (.): no statistical significance, (***): trend significant at α = 0.001.

TN	MAM RCP 2.6	OND RCP 2.6	MAM RCP 8.5	OND RCP 8.5
Trend	0.0032^{O}/year	0.0005^{O}/year	0.0429^{O}/year	0.0366^{O}/year
Significance α	(.)	(.)	(***)	(***)
TX	MAM RCP 2.6	OND RCP 2.6	MAM RCP 8.5	OND RCP 8.5
Trend	-0.0006^{O}/year	0.0055^{O}/year	0.0457^{O}/year	0.0315^{O}/year
Significance α	(.)	(.)	(***)	(***)

ADDENDUM 2: FIGURES

A. Performance of the RegCM 4.7 for TX and TN during MAM and OND

A1. Observed and simulated TX during MAM and OND

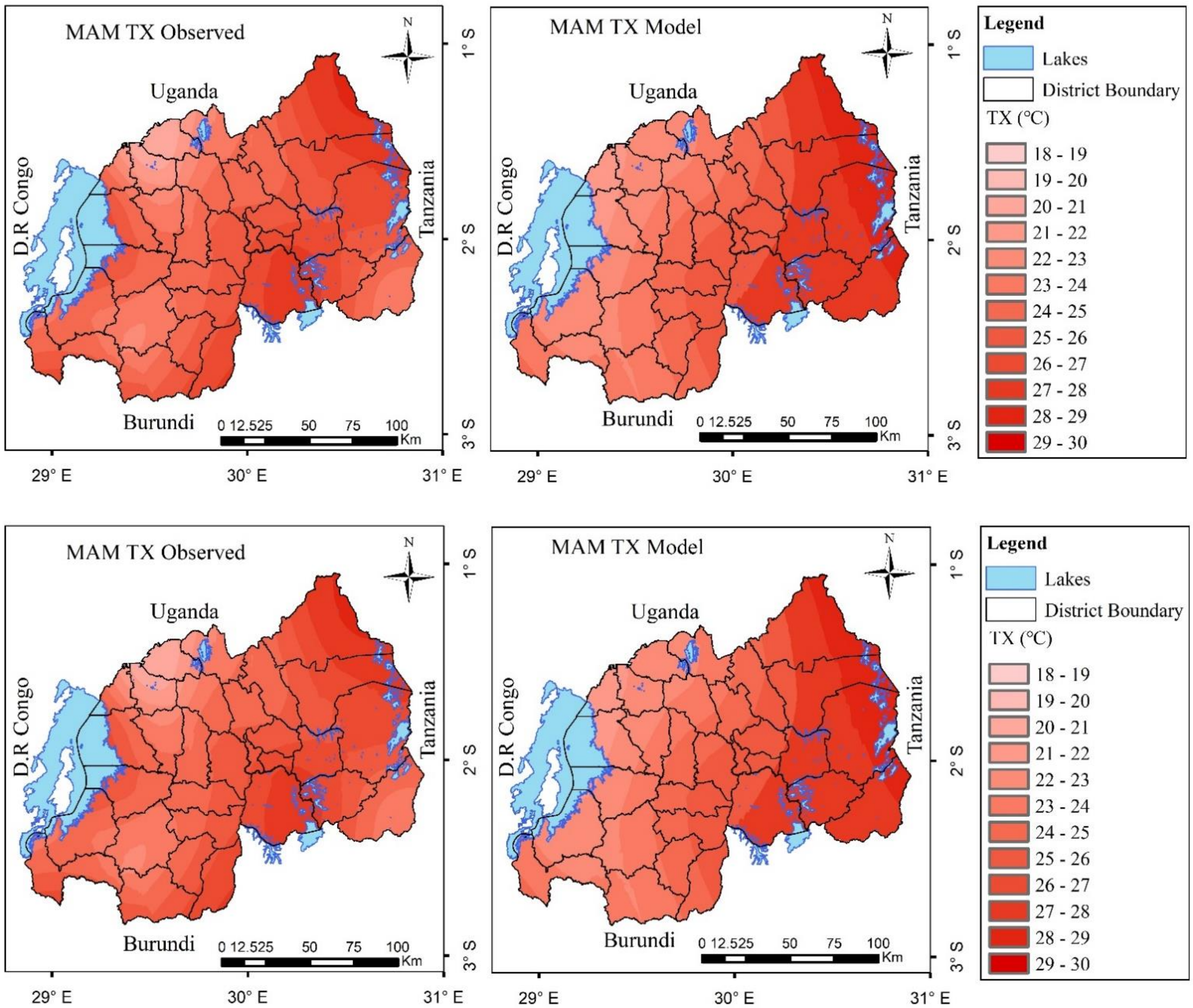

Figure 4.1: Comparison of observed and simulated seasonal mean TX over Rwanda from 1983-2005.

A2. Observed and simulated TN during MAM and OND

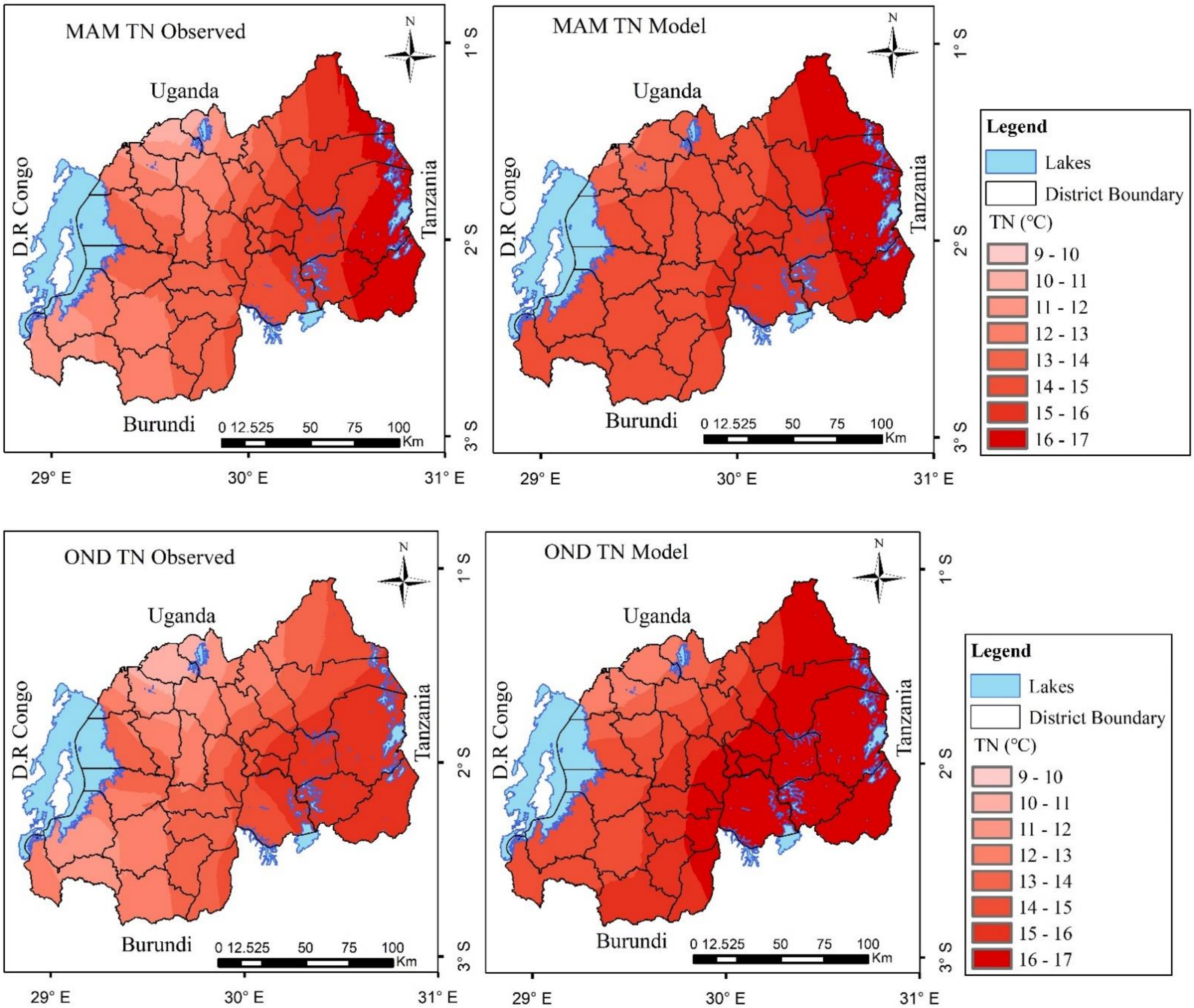

Figure 4.2: Comparison of observed and simulated seasonal mean TN over Rwanda from 1983-2005.

B. Root Mean Square Error and BIAS

B1.Root Mean Square Error and BIAS for TX during MAM and OND

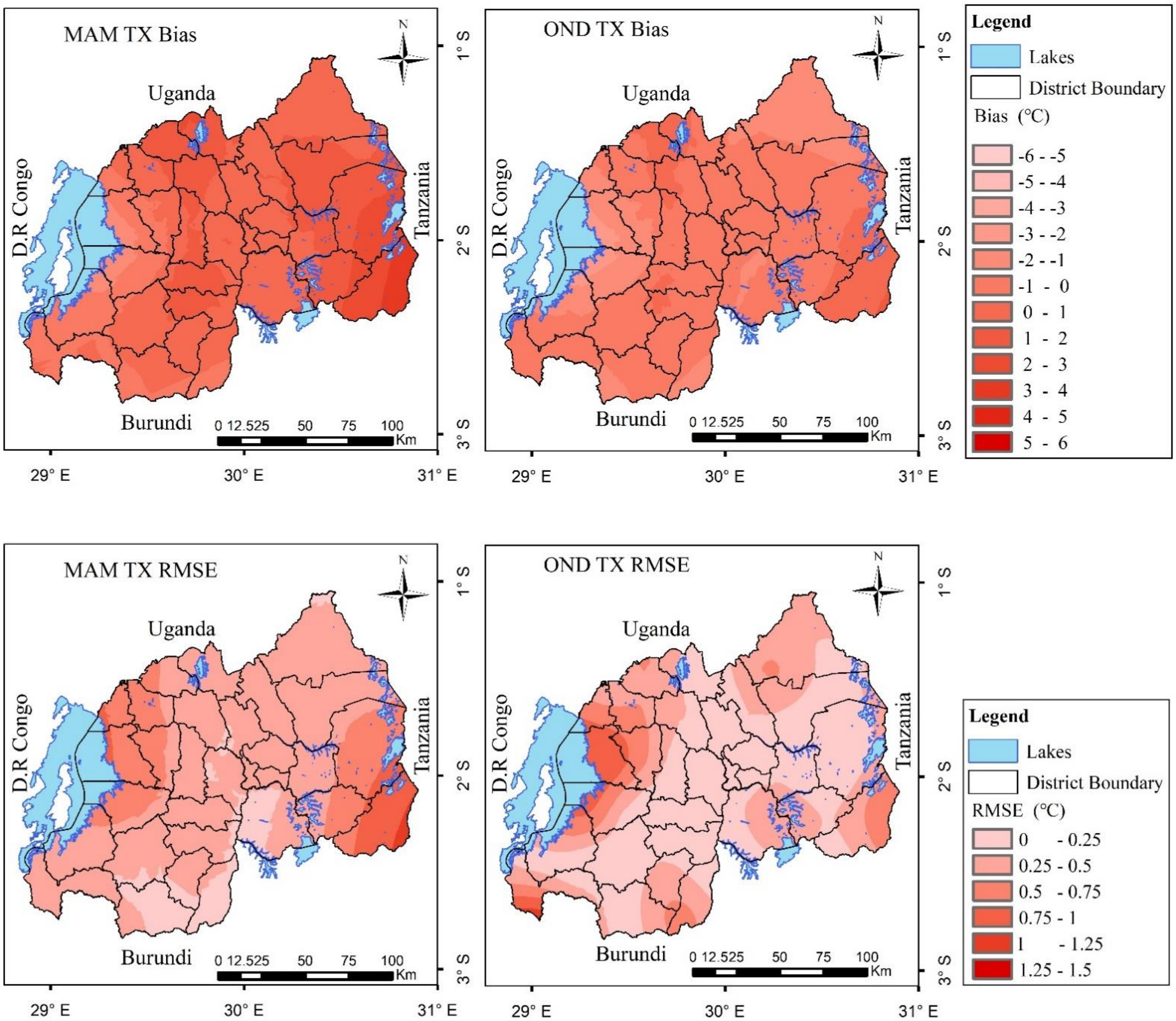

Figure 4.3: Bias and Root Mean Square Error of seasonal mean temperature relative to seasonal mean of observed TX over Rwanda from 1983-2005.

B2.Root Mean Square Error and BIAS for TN during MAM and OND

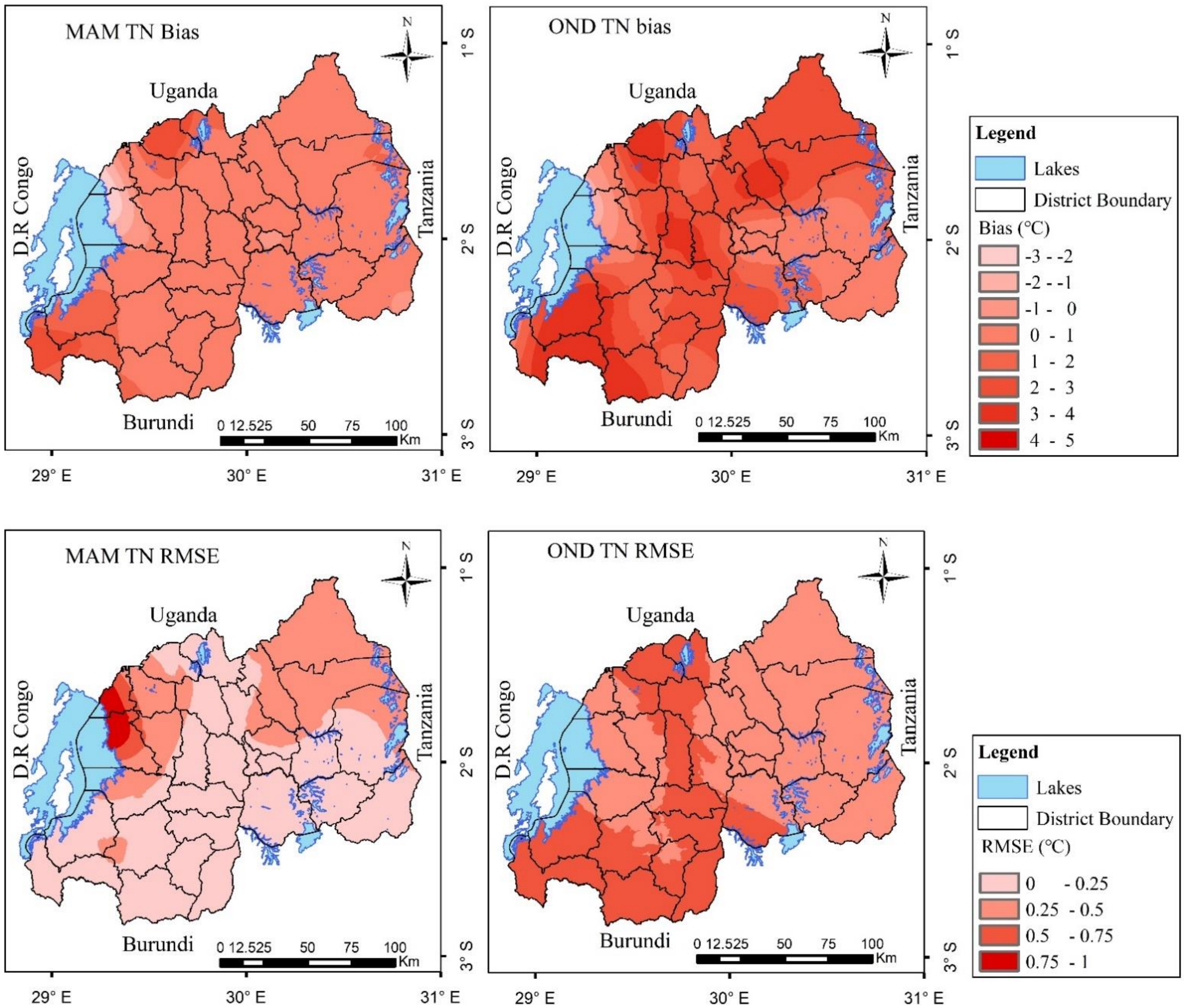

Figure 4.4: Bias and Root Mean Square Error of seasonal mean temperature relative to seasonal mean of observed TN over Rwanda from 1983-2005

C. Inter Annual variability

C1. Observed and Simulated TN Standardized anomaly

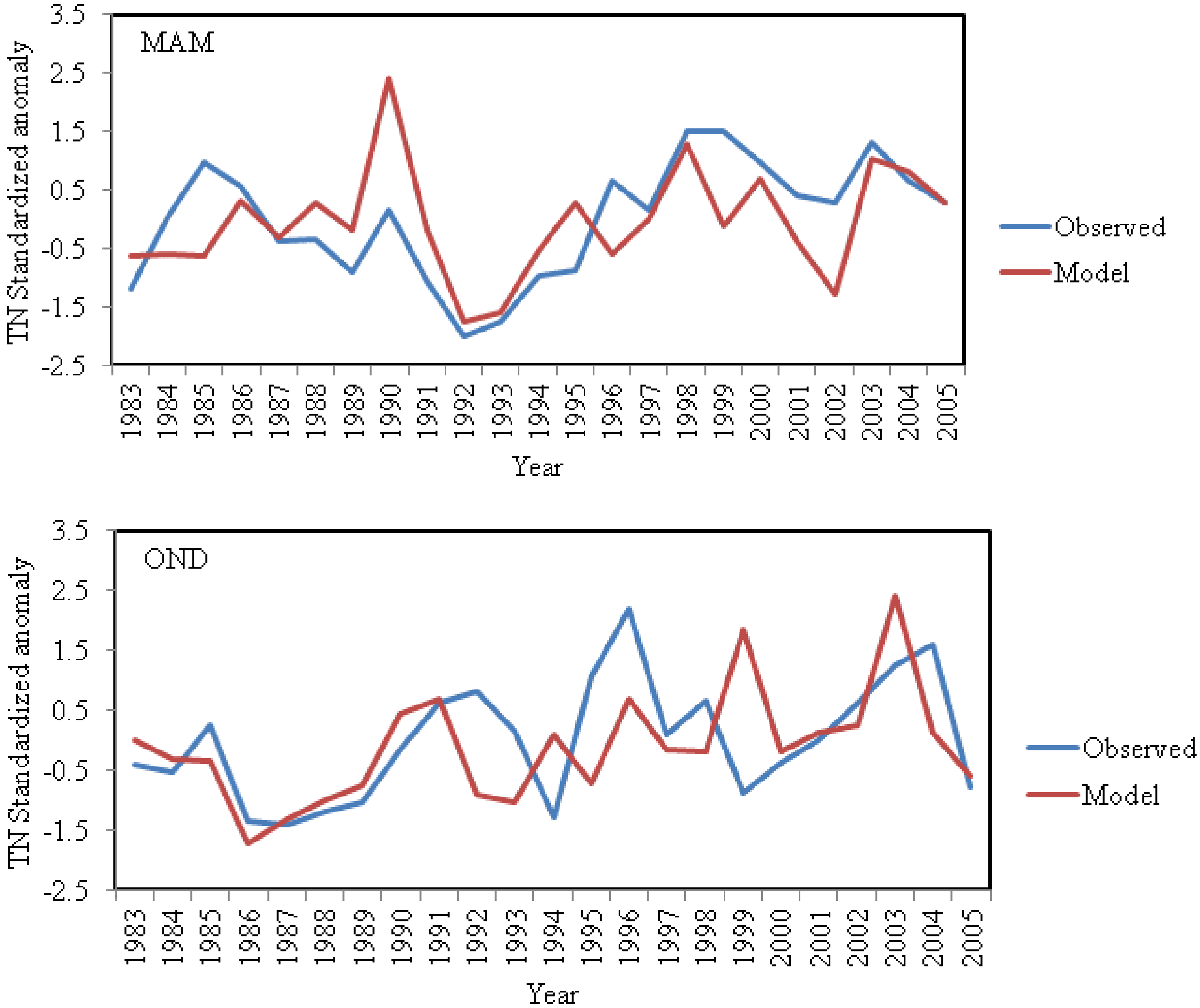

Figure 4.5: Standardized TN anomalies (indices) for MAM (top) and OND (bottom) of observed and model simulation averaged over Rwanda from 1983-2005.

C2. Observed and Simulated TX Standardized anomaly

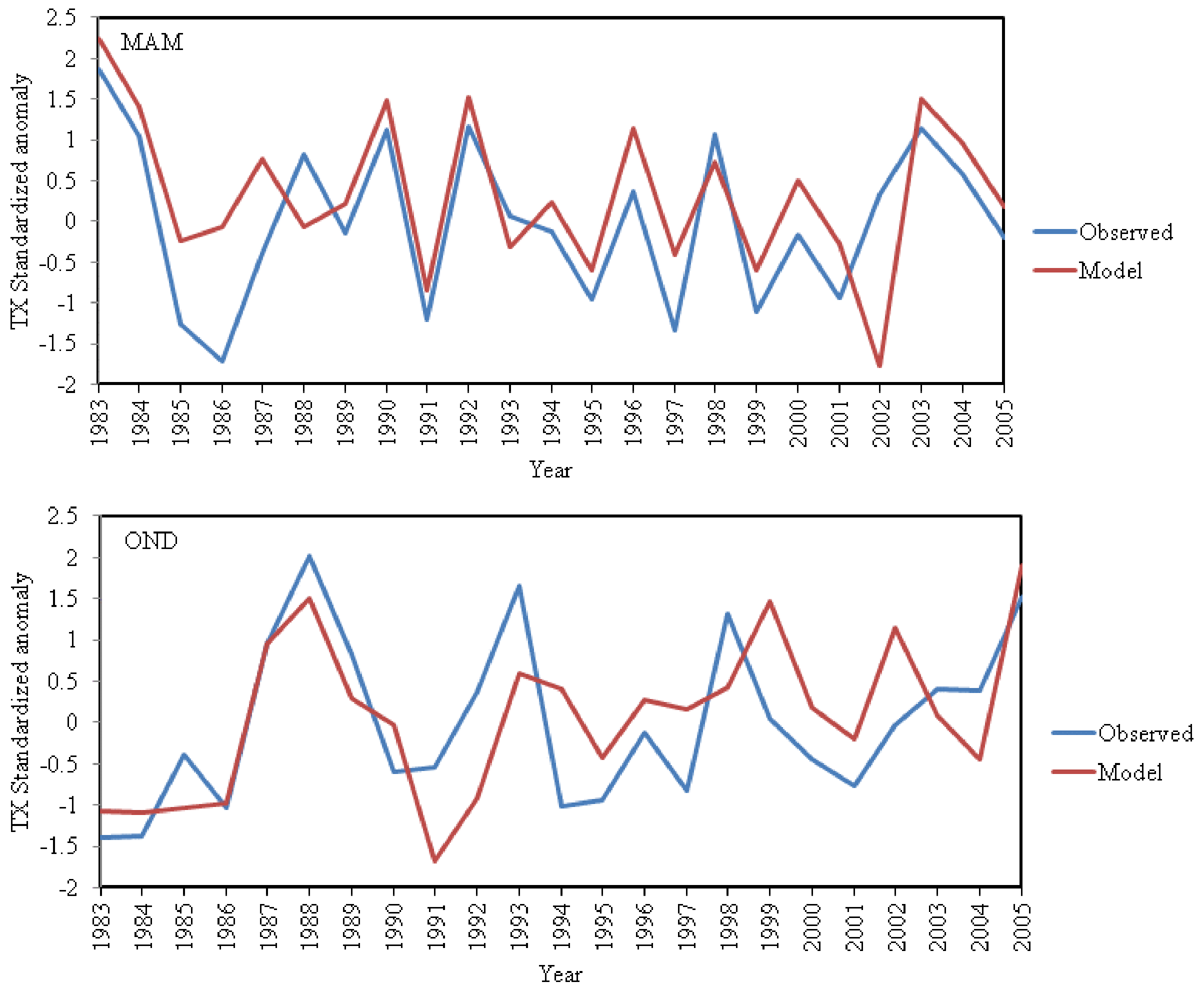

Figure 4.6: Standardized TX anomalies (indices) for MAM (top) and OND (bottom) of observed and model simulation averaged over Rwanda from 1983-2005.

D. Projected temperature

D1. Projected Maximum Temperature for MAM and OND

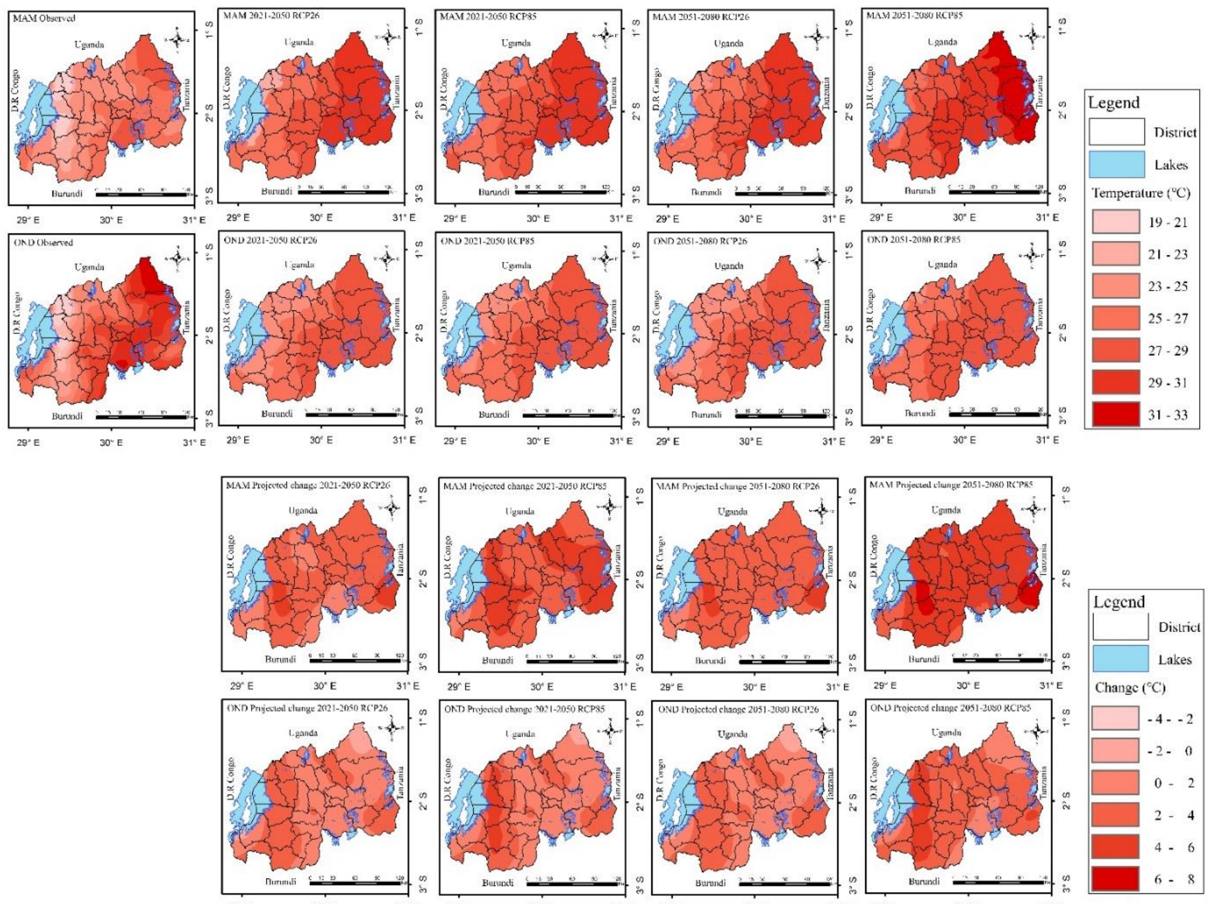

Figure 4.7: Projected maximum temperature (2021-2050) and (2051-2080) using RCP2.6 and RCP8.5 from RegCM 4.7 model during MAM and OND rain seasons.

D2. Projected Minimum Temperature for MAM and OND

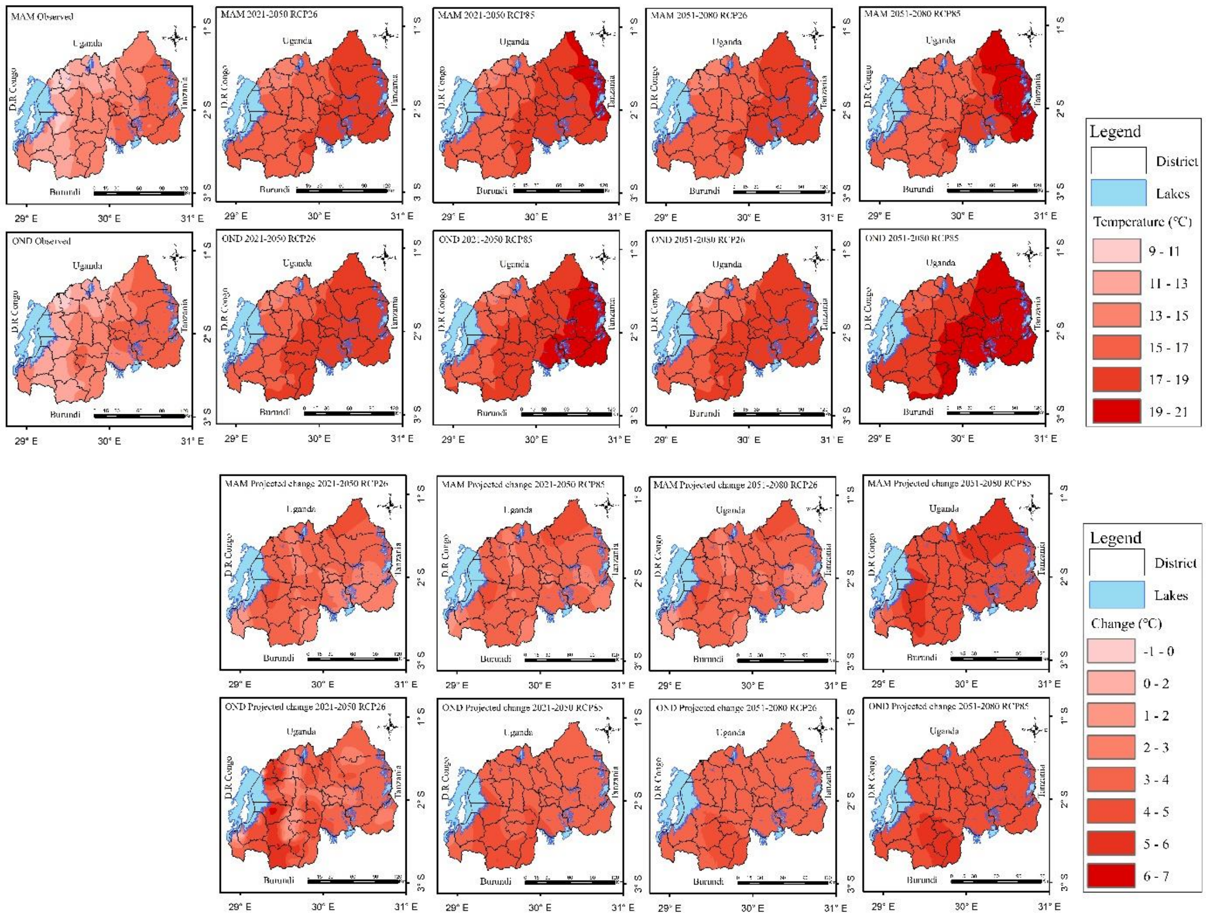

Figure 4.8: Projected minimum temperature (2021-2050) and (2051-2080) using RCP2.6 and RCP8.5 from RegCM 4.7 model during MAM and OND rain seasons.

E. Trend analysis

E1. Trend of maximum temperature for MAM and OND

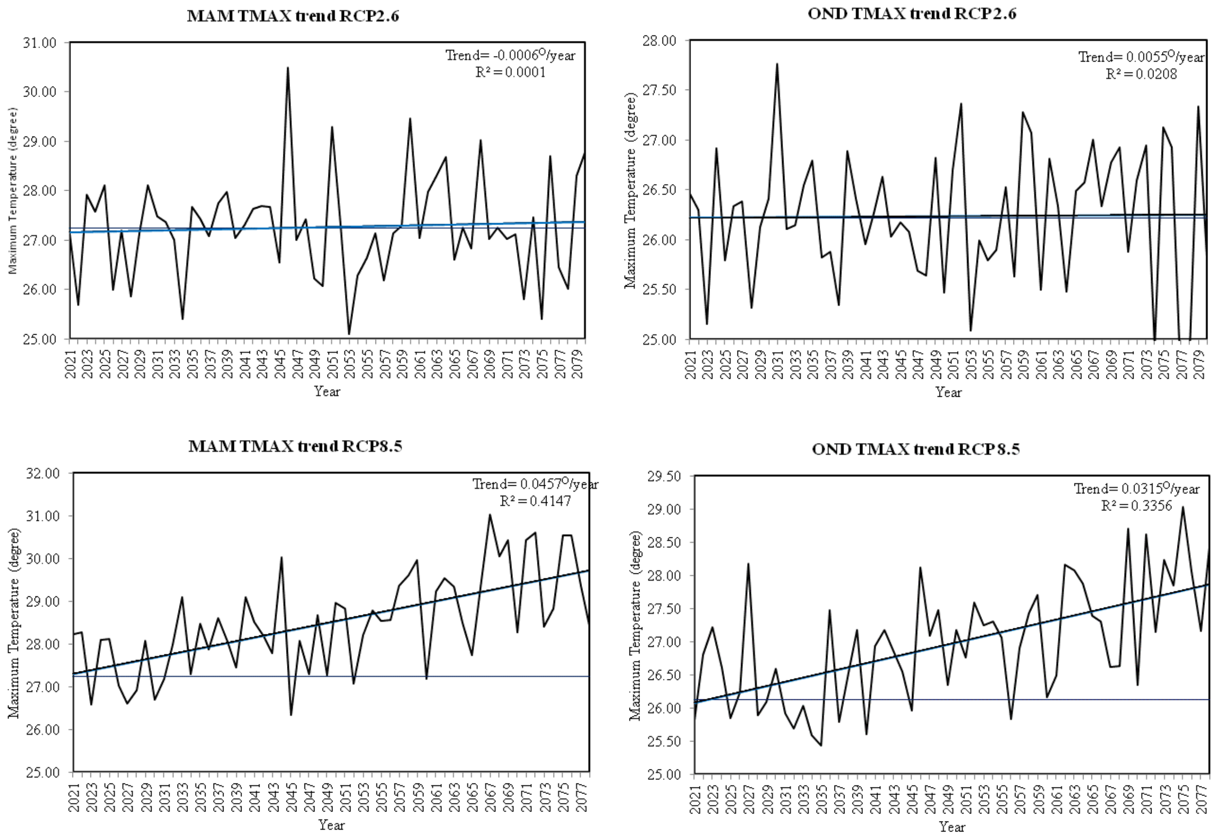

Figure 4.9: Trend of maximum temperature for RCP 2.6 and RCP 8.5 scenarios for the period 2021-2080.

E2. Trend of minimum temperature for MAM and OND

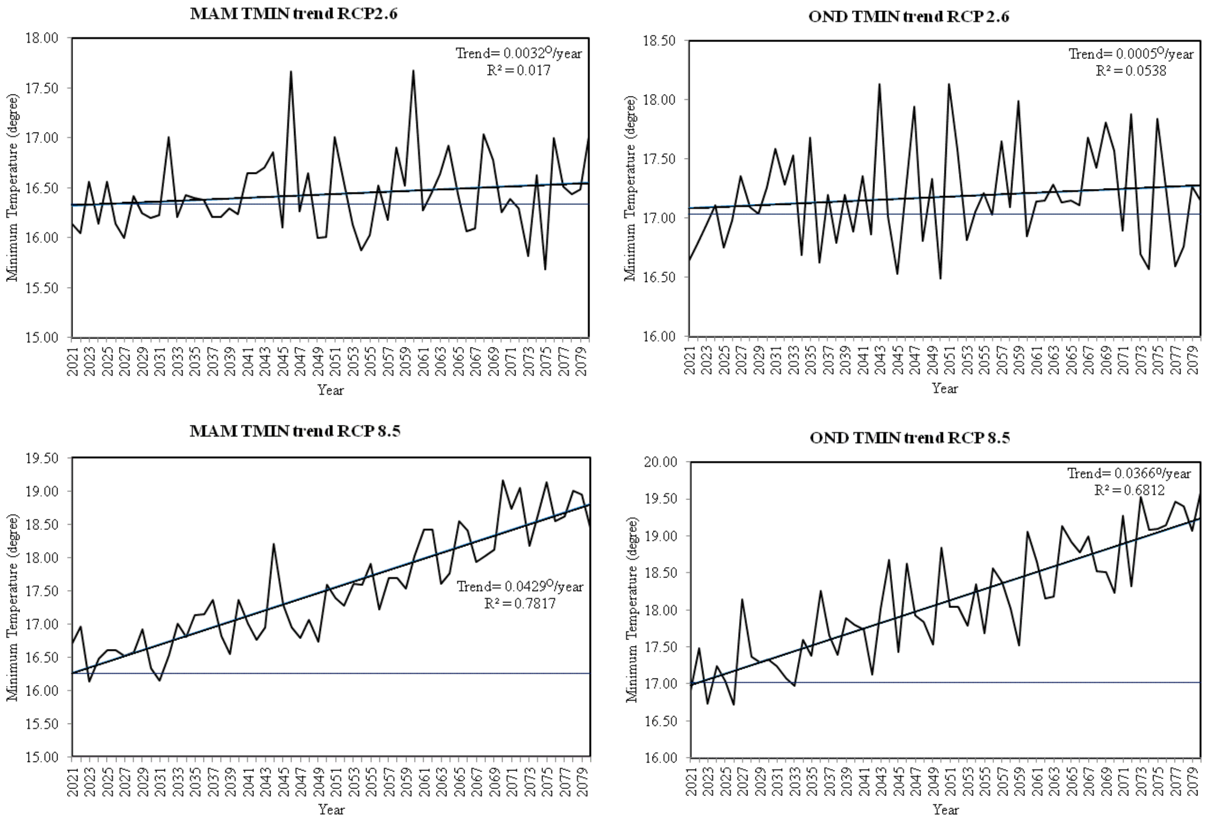

Figure 4. 10: Trend of minimum temperature for RCP 2.6 and RCP 8.5 scenarios for the period 2021-2080.

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