African Journal of Climate Change and Resource Sustainability, Volume 3, Issue 1, 2024
Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

African Journal of Climate Change and Resource Sustainability
ajccrs.eanso.org
Volume 3, Issue 1, 2024
Print ISSN: 790-962X | Online ISSN: 790-9638
Title DOI: https://doi.org/10.37284/2790-9638

EAST AFRICAN NATURE & SCIENCE ORGANIZATION

Original Article

Testing CORDEX GCMs for Projecting Rainfall in Amhara, Ethiopia

Antensay Mekoya[1] & Moges Molla[1]*

[1] Ethiopian Forest Development, P. O. Box 2128, Bahir Dar, Ethiopia.
[*] Author for Correspondence ORCID ID: https://orcid.org/0000-0002-2895-4581; Email: antensaymekoya@yahoo.com

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

Date Published:

31 January 2024

Keywords:

Climate Change Modelling, Model Bias Correction, Rainfall Projection, Model Validation.

ABSTRACT

Five CORDEX Global Circulation Models (GCMs): ICHEC-EC-EARTH, MIROC5, HadGEM2-ES, MPI-ESM-LR, and NorESM1-M were tested and validated for projecting rainfall in the Amhara regional state of Ethiopia. The GCMs were evaluated in terms of their performance during the historical period 1981-2020 and of the near-term, mid-term, and long-term future periods in three Representative Concentration Pathway (RCP) scenarios, RCP2.6, RCP4.5, and RCP8.5, across 71 grid points. Monthly observed rainfall data was used to compare the GCMs' performance and correct their biases using three non-parametric quartile mapping methods: robust empirical quartiles, empirical quartiles, and smoothing splines. The results show that HadGEM2-ES and MPI-ESM-LR had the best performance in the study area. The test and validation results for these two GCMs have come up with r = 0.8, NSE = 0.5-0.6, and RMSE = 64-70 mm/month. As there was a large discrepancy in historical and projected CORDEX rainfall data, bias correction was necessary, and the robust empirical quartiles method was found the best for the Amhara region. Compared to the historical, there will be a decrease in the monthly rainfall amount for the months of March, May, June, July, and October and an increase for the rest in all projected scenarios. The result concluded that using an ensemble of HadGEM2-ES & MPI-ESM-LR GCMs would better simulate the rainfall in the Amhara region.

APA CITATION

Mekoya, A. & Molla, M. (2024). Testing CORDEX GCMs for Projecting Rainfall in Amhara, Ethiopia *African Journal of Climate Change and Resource Sustainability*, *3*(1), 24-48. https://doi.org/10.37284/ajccrs.3.1.1730.

CHICAGO CITATION

Mekoya, Antensay and Moges Molla. 2024. “Testing CORDEX GCMs for Projecting Rainfall in Amhara, Ethiopia”. *African Journal of Climate Change and Resource Sustainability* 3 (1), 24-48. https://doi.org/10.37284/ajccrs.3.1.1730

HARVARD CITATION

Mekoya, A. & Molla, M. (2024) “Testing CORDEX GCMs for Projecting Rainfall in Amhara, Ethiopia”, *African Journal of Climate Change and Resource Sustainability*, 3(1), pp. 24-48. doi: 10.37284/ajccrs.3.1.1730.

IEEE CITATION

A. Mekoya & M. Molla. “Testing CORDEX GCMs for Projecting Rainfall in Amhara, Ethiopia”, AJCCRS, vol. 3, no. 1, pp. 24-48, Jan. 2024.

MLA CITATION

Mekoya, Antensay & Moges Molla. “Testing CORDEX GCMs for Projecting Rainfall in Amhara, Ethiopia”. *African Journal of Climate Change and Resource Sustainability*, Vol. 3, no. 1, Jan. 2023, pp. 24-48, doi:10.37284/ajccrs.3.1.1730.

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

INTRODUCTION

In Ethiopia, the current climate change monitoring systems are inadequate for supporting growth and sustainable development because the climate systems are not fully understood. Moreover, it is oriented more toward basic climate science, weather forecasting, meteorology, and global interests than climate impacts (Abbass et al., 2022). The frequency of occurrence of extreme weather incidents, including fluctuation of large precipitation patterns, decreasing trends in crop growing periods, and droughts, have been increasing (IPCC, 2019; Clarke et al., 2022). Shifts in mean rainfall and temperature combined with variability in sea levels, air temperature, precipitation, floods, and droughts intensity and frequency have been encountered across the globe (ACPC, 2013; ACPC, 2018).

Climate change projections are uncertain due to natural variability in the climate system, an imperfect ability to model the atmosphere's response to any given emissions scenario, a lack of sufficient data, and a lack of tools and models at spatial and temporal scales appropriate for decision-making (ACPC, 2013; EPCC, 2015). Other sources of uncertainty are 1) the lack of enough reliable data and models or tools for temporal and spatial projections of the future climate, 2) the inability of scenario-based models to fully represent GHG emissions and socio-economic activities to the Earth's atmosphere response, and 3) the variability in the climate systems. Ethiopia has a problematic test for climate models due to its geography (Diro et al., 2011). The East African Highlands, such as the Bale and Semien Mountains, split Ethiopia into different climates (Diro et al., 2011). To the north and west, locally called Kiremt, June to September is the primary rainfall season, receiving more of the annual rainfall amount. The February to May rainfall season, locally called Belg, is the second rainy season in most parts of Ethiopia. Belg is known for significant inter-annual and intra-seasonal variabilities (Bekele-Biratu et al., 2018). The contribution of Belg for the annual rainfall amount is up to 40% in central, northeastern, and southwestern Ethiopia and exceeding 50% in southern and southeastern Ethiopia.

October-January is locally called Bega; Bega is a dry season in most parts of Ethiopia. The varying rainfall distribution in different parts of Ethiopia makes the simulation of rainfall in Ethiopia very difficult (Gisila et al., 2015; Shiferaw et al., 2015). However, generating and disseminating reliable climate data and information that are useful for planning adaptation and mitigation strategies for climate variability and change is essential for agriculture and other developmental sectors (ACPC, 2018; UNECA, 2011). Many adaptation and mitigation studies are being conducted in different disciplines in Ethiopia based on the climate model projection data. However, scientific analysis does not support the adoption of models for adaptation and mitigation research based on the reliability of the existing models. Gaps in the projection and monitoring of climate exist in modelling (Michael, 2009). Therefore, for mitigation and adaptation measures against climate change impacts, identifying reliable climate models to predict the near-term and project the long-term climate plays a valuable role in setting policies and strategies. According to IPCC (2019), the increase in global surface temperature is projected to be between 0.6 & 4.0 ^{o}C. Studies conducted in Ethiopia's Abay and Lake Tana basins show that the basins are climate-sensitive (Alaminie *et al*., 2021; Ayalew *et al*., 2022). Ethiopia is vulnerable to climate change and variability because most of the population lives in rural lands where rainfed agriculture is dominant (NMA, 2007). Also, (UNECA, 2011)drought and famine are severe problems in Ethiopia and East Africa (UNECA, 2011; Mera, 2018).

The study highlights the need to address the challenges and limitations associated with climate modelling in the Ethiopian context. This study aims to highlight the importance of screening, testing, and validating climate modelling outputs to ensure their reliability in projecting climate change in Ethiopia. The following problems arise:

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

- Limited Development of Climate Modelling in Ethiopia: Climate modelling in Ethiopia, and even in Africa as a whole, is relatively young and underdeveloped. The lack of significant advancements in climate modelling techniques and resources poses a challenge to accurately project climate change impacts in the region.

- Shortage of Climate Modelling Specialists: Ethiopia has a significant shortage of climate modelling specialists. The limited pool of experts with the necessary skills and knowledge to utilize climate models effectively hinders the country's ability to generate reliable and accurate projections of future climate scenarios.

- Inadequate Resources for Climate Modelling: Insufficient technological and financial resources pose a significant obstacle to conducting comprehensive climate modelling studies in Ethiopia. The scarcity of high-quality data, computing power, and research funding limits the capacity to develop and validate robust climate models specific to the Ethiopian context.

- Importance of Screening, Testing, and Validation: The process of screening, testing, and validating climate modelling outputs is crucial for ensuring the accuracy and reliability of projections. Without rigorous evaluation and verification, the outputs may suffer from biases, uncertainties, and limitations, leading to flawed policy decisions and ineffective adaptation strategies.

- Implications for Various Sectors: Reliable climate models have essential implications for numerous sectors in Ethiopia, including agriculture, water resources, forestry, infrastructure development, and disaster management. Inaccurate projections can result in inadequate planning, vulnerability to climate risks, and sub-optimal resource allocation (Alemayehu & Bewket, 2017).

It is crucial to rely on accurate and reliable climate projections to inform decision-making processes, minimize risks, and develop effective climate change adaptation and resilience strategies in Ethiopia (Lemi & Hailu, 2019). Climate projections play a crucial role in water resources management. Inaccurate projections can result in incorrect estimations of future water availability, leading to improper planning of water infrastructure, inefficient water allocation, and challenges in managing water scarcity or excess. This can impact drinking water supply, irrigation systems, hydropower generation, and overall water security (Cheung et al., 2008). Addressing these problems and conducting rigorous screening, testing, and validating climate modelling outputs is paramount. By improving the quality and reliability of climate projections specific to Ethiopia, policymakers, researchers, and stakeholders can make informed decisions and develop effective strategies to mitigate the adverse impacts of climate change in the country.

Global Circulation Models (GCMs) can be used to simulate climate based on Representative Concentration Pathways (RCPs) for modeling current and future climate change. In this study, selected currently operational GCMs were tested and validated, and the most reliable models for projecting rainfall in Amhara were identified. Thus, this study aimed to provide reliable past, historical, present, and future climate data that satisfies the needs of decision-makers, researchers, development planners, and practitioners. From regional climate models over CORDEX Africa, Akinsanola et al. (2015) found that RCA and REMO fairly simulate West African rainfall adequately, particularly Summer Monsoon precipitation. In this study, RCA regional climate model was used.

Significance

The relevance of this study arises because climate projections are essential for climate change mitigation and adaptation, disaster risk management, and planning and policy-making, such as planning agricultural activities. Due to the complex nature of the climate system, past climate trends may vary and may not continue in the future. Global climate models, also called Global

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

Circulation Models, (GCMs) are used to project the future climate. GCMs can capture major large-scale features; however, they have problems giving precise details for small-scale features. In this regard, regional climate models (RCMs) are preferable. Therefore, the relevance of this study is to identify the most reliable models (GCMs and RCMs) that can be used for projecting precipitation of the Amhara regional state of Ethiopia until 2100, where 2021–2040, 2041–2060, and 2081–2100 are considered as near term, mid-term, and long term, respectively (Lee et al., 2021). At the end of this study, information and technologies will be made available for researchers, development planners, implementers, and policymakers. Thus, they are considered the beneficiaries of the study. Reliable climate models will be beneficial for developing and exploring climate data for research and planning purposes. Information and technologies regarding extreme climate events will become necessary for the government and society to plan and implement mitigation and adaptation measures to tackle the adverse impacts of climate change. Continuous GHG emissions monitoring will benefit Ethiopia in controlling the most contributing sector to keep its development trajectory in the green development strategy framework and achieve the ambitious goal of having net zero emissions by 2025. The output of the study includes reliable GCMs that will be used for the rainfall projection by research communities involved in climate impact assessments. The study's outcome includes reliable climate data and information to be used by researchers, development planners, and policymakers. The findings of this study will be useful input information for water resources, agriculture, irrigation, and forestry development and management practices in Amhara, Ethiopia.

Objectives

General objective:

- Providing historical, present, and future rainfall information to support agriculture, forestry and water resource managements in the Amhara regional state of Ethiopia.

Specific objectives:

- Identifying the best bias correcting method and correcting rainfall data biases (errors) of CMIP5 CORDEX Global Circulation Models in three RCP scenarios (RCP 2.6, RCP 4.5, and RCP 8.5).
- Screening, testing, validating, and identifying the most reliable Global Circulation Models for projecting the future rainfall amount of the Amhara regional state of Ethiopia.
- Providing information regarding historical (1981-2020) and future (2021-2100) rainfall data of the Amhara regional state of Ethiopia.

MATERIALS AND METHODS

Study Area

The study area is Amhara National Regional State (see *Figure 1* and *Figure 2*), located in the northwestern and northcentral parts of Ethiopia between latitude 8.8° & 13.64° N and longitude 35.2°& 40.04° E. Amhara region which is divided into 10 administrative zones consisting of 105 woredas (districts) is the second most populous region in Ethiopia (25% of the Ethiopian population resides in Amhara). In 2023, the region had 13 administrative zones, with Gonder and Gojam having four and three distinct districts, respectively. It had a population of 21.1 million in 2017 (UNICEF, 2018; Birara et al., 2018). Amhara has enormous water and livestock resources, 90% of which are in rural parts engaged in subsistence crop and livestock agriculture activities (CSA, 2007). It has a total area of about 170,000 km^2 of which about 156,000 km^2 is mountainous (Sisay *et al.*, 2016; Birara et al., 2018). Its altitude ranges from 700 m in the eastern part to 4620 m a.s.l.(at Ras Dashen, the highest peak in Ethiopia) in the north-west (Birara et al., 2018).

Dividing a country or a state into climate boundaries instead of following political or state boundaries will make climate studies more effective. Thus, in this study, the Amhara regional state is further subdivided into five rainfall shape regimes (A3 to A6), as precisely represented in

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

Figure 2. In Ethiopia, a day's rainfall is the total amount from that day at 7 am until the next day at 7 am; the measurement is taken or recorded on the next day at 7 am. A wet or rainy day is defined as a day with ≥0.1 mm of precipitation (Harris et al., 2020). This study defines a rainy day as a day with greater than 0.1 mm of rain in a day or within 24 hours (Seleshi & Zanke, 2004). In warm tropical regions like Ethiopia, the definition of rainy days by Seleshi and Zanke (2004) is preferred due to the availability of high evapotranspiration.

Based on altitude variations, the climate of the Amhara region is traditionally divided into three: 1) hot zone or 'Kola,' < 1500 m a.s.l.; covers 31% of the region. 2) warm zone or 'Woyina Dega' (1500 – 2500 m a.s.l.); covers 44% of the region. 3) The cold zone or 'Dega' (2500 - 4620 m a.s.l.) covers 25% of the region (Ayalew et al., 2012). From 1981 to 2020, the region's monthly mean maximum, minimum, and air temperatures were 26.7, 12.5, and 19.6 ˚C, respectively.

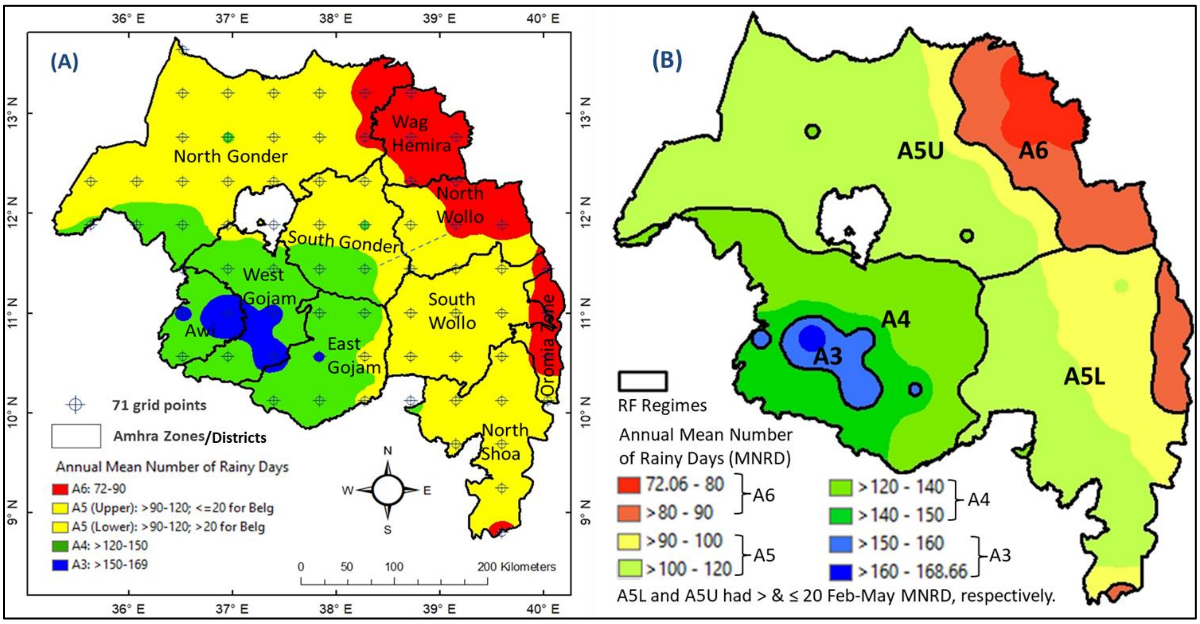
Note: In 2023, the Amhara regional state of Ethiopia is divided into 22 districts or Zones. However, this study has not used the newly modified map of the Amhara regional state of Ethiopia that includes the Wolkait-Tsegele district (located to the north of North Gonder) and Raya district (located to the north of North Wollo and east of Wag Hamira).

Figure 1: Study Area: Amhara regional state of Ethiopia administrative map

Source: (UNOCHA, 2018)

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

Figure 2: Rainfall shape regimes of Amhara, Ethiopia



Data

The Coordinated Regional Climate Downscaling Experiments (CORDEX) project for Africa (AFR- 44) (https://climate4impact.eu/impactportal/data/esgfsearch.jsp#) has around 10 Regional Climate Models (RCMs) such as 1) CanRCM4 2) CCLM4-8-17 3) CRCM5 4) HadGEM3-RA 5) HadRM3P 6) HIRHAM5 7) RACMO22T 8) RCA4 9) RegCM4-3 10) REMO2009. The Rossby Centre Regional Atmospheric Model version 1 (RCA4_v1) is one of the most widely used and recommended reliable RCM in Africa (Akinsanola *et al*., 2015; Demissie & Sime, 2021; Tamoffo et al., 2021; Martel *et al*., 2022; Mutayoba & Kashaigili, 2017; Tang et al., 2019; Ogega & Gyampoh, 2020; Ogega et al., 2020; Kebede *et al*., 2013; Dosio et al., 2022a). Thus, from the above ten RCMs, RCA4_v1 was used throughout this study.

The above ten RCMs are driven by fourteen deriving models (GCMs used to force RCMs). That means, for example, RCA4_v1 RCM is derived or forced by fourteen GCMs from Coupled Model Intercomparison Project phase 5 (CMIP5) under three representative concentration pathways (RCP2.6, RCP4.5, and RCP8.5) listed below:

1) CCCma-CanESM2
2) CNRM-CERFACS-CNRM-CM5
3) CSIRO-QCCCE-CSIRO-Mk3-6-0
4) ECMWF-ERAINT
5) ICHEC-EC-EARTH
6) IPSL-IPSL-CM5A-LR
7) IPSL-IPSL-CM5A-MR
8) MIROC-MIROC5
9) MOHC-HadGEM2-ES (shortly named in this paper as 'HadGEM2-ES')
10) MPI-M-MPI-ESM-LR (shortly named in this paper as 'MPI-ESM-LR')
11) MPI-M-MPI-ESM-MR
12) NCC-NorESM1-M (shortly named in this paper as 'NorESM1-M')
13) NOAA-GFDL-GFDL-ESM2G
14) NOAA-GFDL-GFDL-ESM2M.

From the above fourteen GCMs that the CORDEX project has, five GCMs have fulfilled the screening criteria, which is having historical and future complete data in RCP 2.6, RCP 4.5, and RCP 8.5 scenarios and in RCA4_v1 r1i1p1 RCM were screened, tested, and validated for projecting

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

rainfall of Amhara regional state of Ethiopia; see *Table 1*.

Table 1: GCMs used in the study

Sn	Code	GCM	RCM	Ensemble*	Country
1	m1	ICHEC-EC-EARTH	RCA4_v1	r1i1p1	Ireland
2	m2	MIROC5	RCA4_v1	r1i1p1	Japan
3	m3	HadGEM2-ES	RCA4_v1	r1i1p1	UK
4	m4	MPI-ESM-LR	RCA4_v1	r1i1p1	Germany
5	m5	NorESM1-M	RCA4_v1	r1i1p1	Norway

**rN, N is the number of ensemble members; iN, N is the number of different initialization states; pN, N is the number of physical parameterizations*

Source: (Herger et al., 2018a and its supplementary materials Herger et al., 2018b; Grose et al., 2023; Demaeyer et al., 2022)

From 144 grid points surrounding the study area with longitude (x) and latitude (y) values ranging from 35.2°, 13.64° at the top left corner to 40.04°, 08.80° at the bottom right corner, 71 grid points enclosed within the study area were used to download GCMs data from CORDEX project (AFR-44). The resolution distance between each grid point was 0.44° (48.88 km). For example, rainfall regimes A3, A4, A5L & A5U, and A6 were represented by 5, 17, 17, 19, and 13 grid points, respectively (*Figure 2*). Also, forty years (1981-2020) of daily rainfall data obtained from the Ethiopia Meteorology Institute (EMI), formerly known as the National Meteorological Agency of Ethiopia (NMA), was used to validate the five GCMs.

Microsoft Excel worksheet and R statistical software packages were used for data analysis and graphics. For Network Common Data Form (NetCDF) data analysis, Climate Data Operator (CDO) was used in the Windows Subsystem for Linux (WSL2) interface; the Ncview operator is used in the Linux (Ubuntu 20.04 LTS) operating system interface. A free, open-source R package, the Climate Data Tool (CDT) created specifically for national meteorological services, was used for grid data analysis.

Methods

The data obtained from the five GCMs were correlated with observed data, and the correlation coefficients and the corresponding statistical significance were obtained to facilitate the comparison of selected climate models. For correlation coefficient. Eq. 1 was applied for each month and selected 71 grid points. The assumption for the model's reliability was based on the strength of the correlation coefficient with statistical significance and least square error. A higher correction coefficient with statistical significance and the least square error signifies higher reliability of the model to simulate the observed data. The statistical t-test (Eq. 2) was applied to test the significance of the correlation coefficients.

$$r = \frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\left[\sum_{i=1}^{n}(O_i - \bar{O})^2\right]}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}} \quad (1)$$

Where O_i is the i^{th} observation for the constituent being evaluated, P_i is the i^{th} simulated value for the constituent being evaluated, n is the total number of observations, and the overbar denotes the mean for the entire evaluation period.

$$t = \frac{r\sqrt{N-2}}{\sqrt{1-r^2}} \quad (2)$$

Where t is the student's test, r is the correlation coefficient, and N is the sample size.

To test the significance of the correlation, the built-in function 'cor.test' using the non-parametric method = "Kendall" was used in the RStudio platform. Also, using the results of Eq. 1 and Eq. 2 in MS Excel formula: 'p-value = DIST (x, deg_freedom, tails)' were used, where x is t value, deg_freedom = N-2; N is the sample size.

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

The future climate of the 2030s (2021-2040), 2050s (2041-2060), and 2080s (2081-2100) were projected using an ensemble of the most reliable GCMs. The results were georeferenced, interpolated, and mapped using ArcGIS 10.8. The inverse distance weighting (IDW) interpolation method was used for spatial mapping. The general formula for IDW interpolation is formed as a weighted sum of the data, see Eq. 3, in which $Z(s_i)$ is the measured value at the i^{th} location, λ_i is an unknown weight depending on the distance between the known and the prediction location, s_o is the prediction location and N is the number of measured values.

$$Z(S_o) = \sum_{i=1}^{N} \lambda_i Z(s_i) \qquad (3)$$

The station data from the Ethiopia Meteorology Institute were downscaled to CORDEX data grid resolution. It was used as a reference to compare the performance of the five climate models (GCMs) and to correct rainfall model data biases using non-parametric quantile mapping (QM) implemented in R software using the 'qmap' package in three options: robust empirical quartiles (RQUANT) (c1), empirical quartiles (QUANT) (c2), and smoothing splines (SSPLIN) (c3). For rainfall projection, future rainfall scenarios for the area were extracted using R software from the five GCMs outputs.

In addition to correlation coefficient (r), other model evaluation metrics such as Nash-Sutcliffe efficiency (NSE) and root mean square error (RMSE) were used. RMSE is simply the square root of mean square error (MSE). RMSE and NSE are calculated as given below (see Eq. 4 and Eq. 5):

$$\text{RMSE} = \sqrt{\text{MSE}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2} \qquad (4)$$

$$\text{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}\right] \qquad (5)$$

Where all variables are defined in Eq. 1, the 0 value of RMSE indicates a perfect fit of the model with the observation data. NSE ranges between $-\infty$ and 1.0 (1 inclusive), and values between 0.0 and 1.0 are considered acceptable performance levels, with NSE =1 being the optimal value (Moriasi et al., 2007, p.887).

RESULTS AND DISCUSSIONS

Results

A two-tailed T-test (alpha = 0.05) test and validation results for the correlation analysis showed a significant relation between the CORDEX model data and observed data. Generally, the correlation (r), Nash–Sutcliffe Efficiency (NSE), and Root Mean Square Error (RMSE) results showed that HadGEM2-ES or m3 of the UK and MPI-ESM-LR or m4 of the German GCMs were the best models for simulating the rainfall of Amhara from the five GCMs used in this study (see *Table 2*). The result also showed that for each of the five GCMs, the first climate model output bias correction method (c1) was the best method, followed by c2 in correcting the GCMs biases in the rainfall data of Amhara (see *Table 2*). For all the analyses, the correlation test was significant at a 95% confidence level (at a 5% significant level), i.e., the p-value for each GCMs was less than 0.05, indicating a significant correlation between the GCMs and observed rainfall data. For m3, the low and medium emission scenarios, RCP 2.6 & RCP 4.5, simulated the rainfall of Amhara better than the high emission scenario, RCP 8.5, whereas the opposite is true for m4 (see *Table 2*). In Table 2, m3c1 means m3 or monthly rainfall of the HadGEM2-ES GCM (of UK) after applying c1 (the first bias correction method) and m3c2, m3c3, m4c1, etc are interpreted in a similar way.

Compared to the historical mean rainfall amount of Amhara, the near-term, mid-term, and long-term Jun-Sep (Kiremt) rainfall will be higher in all scenarios (RCP 8.5, RCP 4.5, and RCP 2.6) except for long-term future (2081-2100) in RCP 8.5 scenario (see *Appendix 1*). However, care has to be taken in considering or applying the result of this study to a particular area. For example, August rainfall in Amhara will increase in all future periods (near-term, mid-term, and long-term) and the three RCPs. However, for the A6 regime of Amhara, August rainfall will decrease

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

in all future periods and all RCPs except for the long-term future (2081-2100) in the RCP 4.5 scenario. Also, the result shows that the dry season or Bega (Oct-Jan) rainfall will increase in the future periods in the three RCPs, particularly in regime A6 (eastern part of Amhara). In Regime A6, the minor rainy season or Belg (Feb-May) will receive less rainfall as compared to the climatological mean, 103 mm, in the future periods in the three RCPs except for the long-term future (2081-2100) in the RCP 2.6 scenario.

Table 2: Comparison of GCMs in simulating monthly rainfall of Amhara, Ethiopia

(Test Result; 1981-2005)					(Validation Result; 2006-2020)				
GCMs	**r**	**NSE**	**RMSE**	**Rank**	**GCMs**	**r**	**NSE**	**RMSE**	**Rank**
m3c1	0.7883	0.574	64.0	1	m3c1 in RCP4.5	0.782	0.584	67.05	1
m3c2	0.7877	0.571	64.2	2	m3c1 in RCP2.6	0.777	0.559	68.20	2
m3c3	0.7800	0.534	66.4	3	m4c1 in RCP8.5	0.776	0.559	68.59	3
m4c1	0.7679	0.530	66.9	4	m4c1 in RCP2.6	0.780	0.548	69.43	4
m4c2	0.7673	0.529	67.1	5	m4c1 in RCP4.5	0.768	0.554	69.36	5
m4c3	0.7654	0.517	67.8	6	m3c1 in RCP8.5	0.773	0.554	69.57	6
m2c1	0.7002	0.397	76.0	7	m5c1 in RCP4.5	0.750	0.494	72.04	7
m2c2	0.6995	0.395	76.2	8	m5c1 in RCP8.5	0.747	0.509	72.58	8
m5c1	0.6937	0.395	76.5	9	m5c1 in RCP2.6	0.727	0.483	73.86	9
m5c2	0.6934	0.393	76.6	10	m2c1 in RCP4.5	0.714	0.446	75.51	10
m3	0.7774	-0.455	127.7	11	m1c1 in RCP2.6	0.722	0.425	77.85	11
m5c3	0.6886	0.367	78.3	11	m2c1 in RCP8.5	0.700	0.433	78.00	12
m1c1	0.6830	0.361	78.6	13	m1c1 in RCP8.5	0.696	0.410	80.65	13
m2c3	0.6896	0.318	79.6	14	m2c1 in RCP2.6	0.676	0.397	80.09	14
m1c2	0.6824	0.359	78.7	15	m1c1 in RCP4.5	0.669	0.352	83.70	15
m4	0.7557	-2.233	135.7	16					
m1c3	0.6777	0.334	80.3	17					
m2	0.6856	-1.897	135.8	18					
m5	0.6662	-1.488	129.7	19					
m1	0.6834	-2.675	147.5	20					

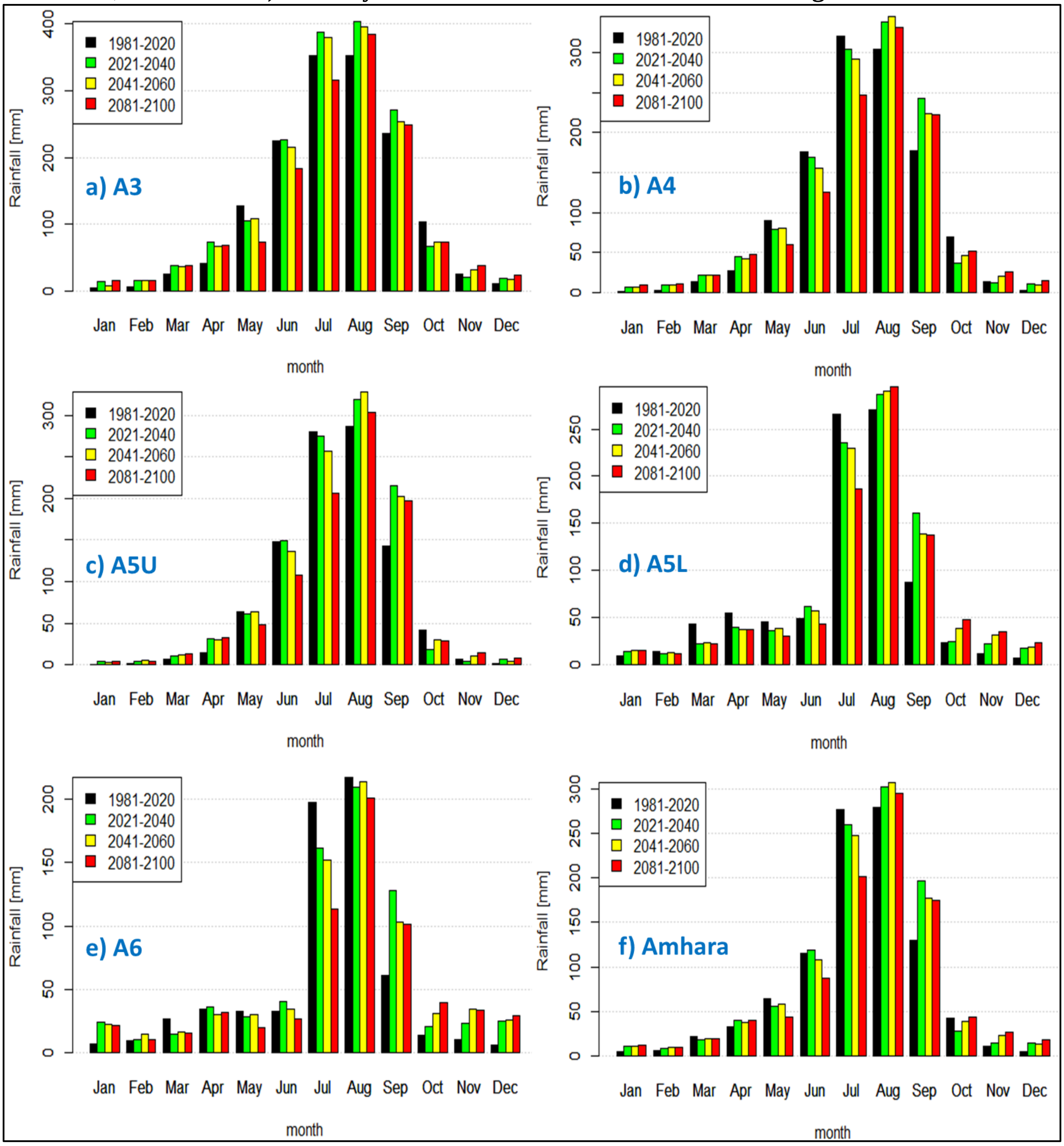
Rank denotes the rank of the average rank of correlation (r), NSE, and RMSE used to compare the five GCMs.

Generally, Amhara's amount and pattern of rainfall were similar in the three RCPs; this was more evident in RCP 4.5 and RCP 2.6 (see *Figures 3-5*). The May-July rainfall amount in Amhara showed a general decreasing pattern from historical to future periods in the three RCPs. In September, the future rainfall of Amhara will be increased by at least 30 mm in all RCPs compared to the historical (see *Figures 3-5*).

For instance, the spatial distribution of historical and future rainfall of Amhara for medium emission scenario (RCP 4.5) is shown in *Figure 6*. Generally, the future annual, June-September (Kiremt), and February-May (Belg) rainfall amounts and their distribution will not be significantly different from the historical. However, compared to the historical rainfall, the October-January season (Bega) will have more rainfall in the southeastern part of Amhara at and around the Oromia Special Zone.

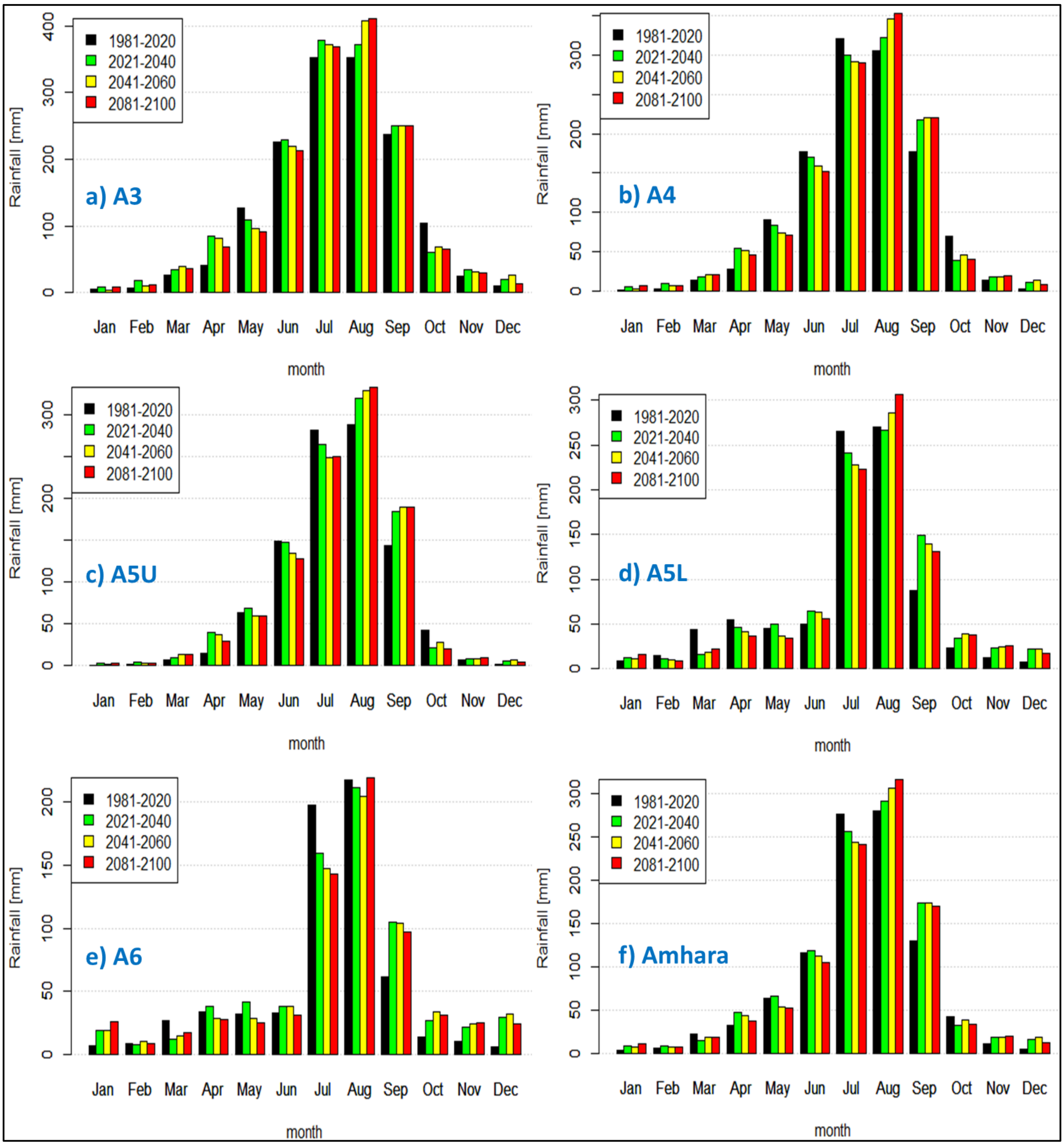
Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

Figure 3: Historical (1981-2020) and future (ensemble of m3 & m4 in RCP 8.5 for 2021-2040, 2041-2060, & 2081-2100) monthly mean total rainfall amount [mm] in Regimes of Amhara



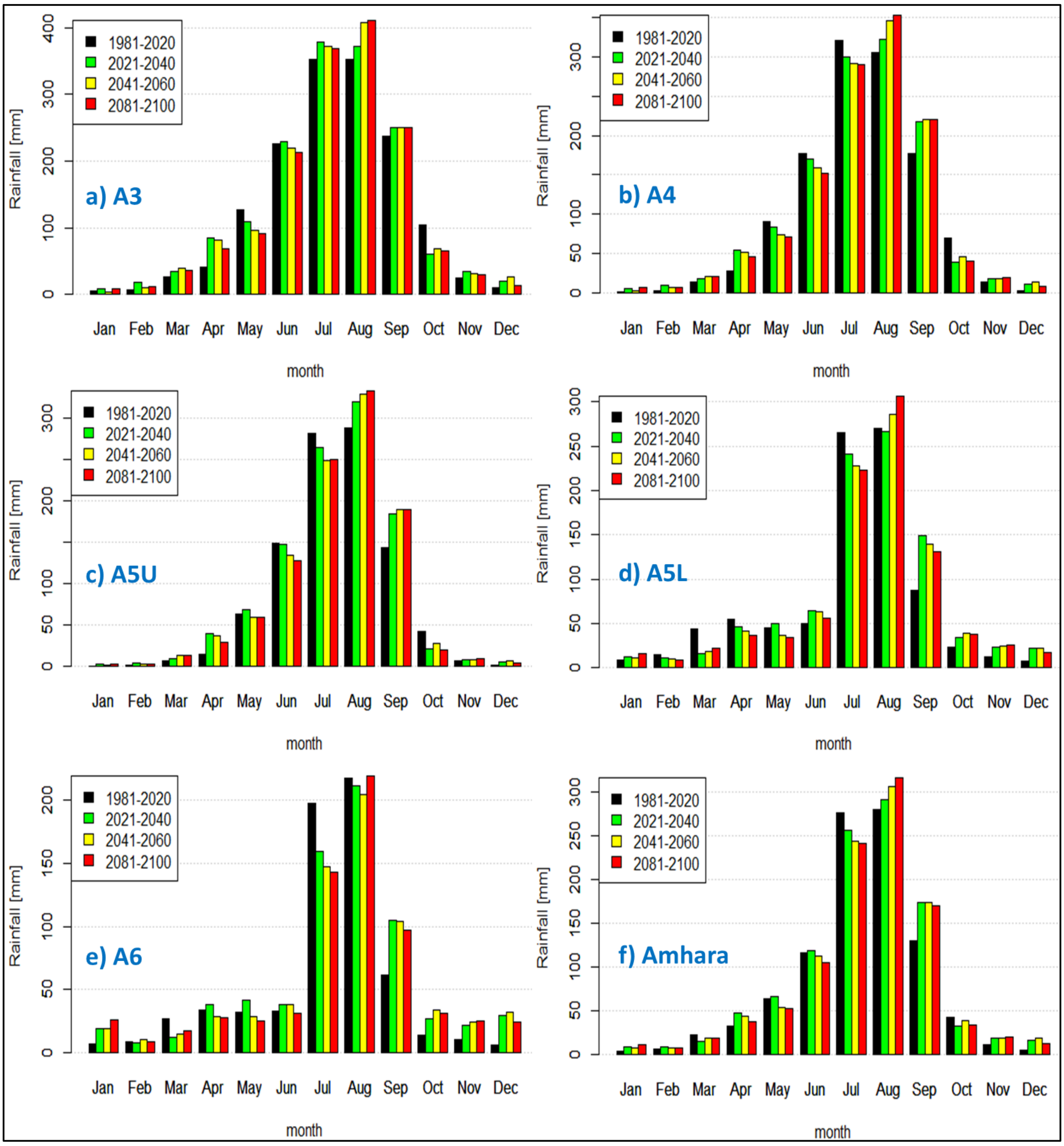
Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

Figure 4: Historical (1981-2020) and future (ensemble of m3 & m4 in RCP 4.5 for2021-2040, 2041-2060, & 2081-2100) monthly mean total rainfall amount [mm] in Regimes of Amhara



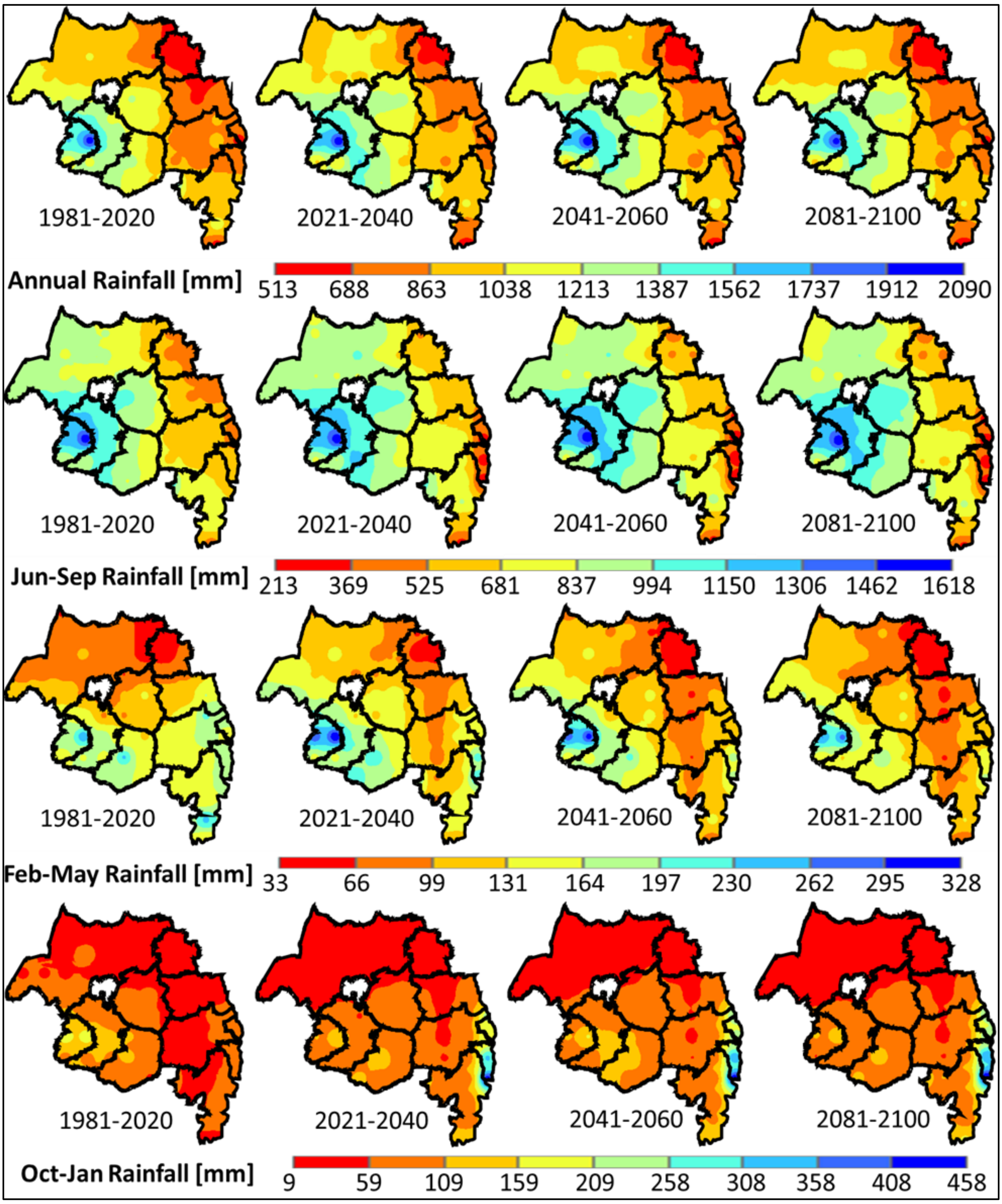
Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

Figure 5: Historical (1981-2020) and future (ensemble of m3 & m4 in RCP 2.6 for2021-2040, 2041-2060, & 2081-2100) monthly mean total rainfall amount [mm] in Regimes of Amhara



African Journal of Climate Change and Resource Sustainability, Volume 3, Issue 1, 2024
Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

Figure 6: Historical (1981-2020) and future (ensemble of m3 & m4 in RCP 4.5 for 2021-2040, 2041-2060, & 2081-2100) Annual, Oct-Jan (Bega), Feb-May (Belg), and Jun-Sep (Kiremt) mean total rainfall amount in Amhara, Ethiopia



Discussions

Based on rainy days and rainfall amount distribution, Ethiopia has three rainfall regimes: Mono-modal, Bi-modal-I, and Bi-modal-II. They are also grouped into five: low, intermediate, moderate, high, and very high rainfall regimes. They are also sub-grouped into twelve sub-rainfall regimes (Berhanu *et al*., 2016). In our study, the rainfall regime of Amhara mainly falls under the category of a high rainfall regime with a Mono-modal pattern. We Subgroup the Amhara regional state into five sub-rainfall regimes aligned with Berhanu *et al*. (2016).

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

For reproducing precipitation, particularly convective precipitation that requires spatiotemporal parameterization, Coupled Model Intercomparison Project Phase 5 and 6 (CMIP5 and CMIP6) climate models' ensembles have limitations over North America (Martel *et al*., 2022). In a similar study, (Li et al., 2021) compared future predictions of annual and extreme precipitation simulations using CMIP6 and CMIP5. In the simulation of total precipitation, they found that CMIP6 has no overall advantage as compared to CMIP5. Most climate projections currently performed by GCMs have been CMIP5 (Navarro-Racines et al., 2020). For example, CMIP5 CORDEX outputs have been used in simulations and projections of future climate by GCMs. Thus, CMIP5 can be used as an alternative to CMIP6.

Navarro-Racines et al. (2020) presented a global database for future climates applying the delta method of climate model bias correction, which reduced 50–70% of climate model bias to be used for impact assessments of climate change in agriculture and biodiversity. In this study, for instance, the first bias correction method, robust empirical quartiles (c1), reduced the RMSE by at least 80%, indicating the necessity of bias correction in climate projection. Dyer et al. (2020) evaluated the CMIP5 ensemble in Ethiopia (Northwest Ethiopia and Awash Basin) to reduce uncertainties for rainfall and temperature data. They found that HadGEM2-AO, GFDL-CM3, and MPI-ESM-MR had the most skill for various categories. According to the result of our study, using an ensemble of the best models (HadGEM2-ES and MPI-ESM-LR) is recommended to reduce the uncertainty that may occur in the rainfall projection of the Amhara regional state of Ethiopia. Using climate projection data and applying the appropriate bias correction method must be performed with great care because uncertainties may exist that may mislead policy planning decisions in agriculture and water resource management.

Deepthi and Sivakumar (2021) used a Compromise Programming (CP) method and Global Performance Indicator (GPI) technique for testing and ranking the ability of 20 GCMs to simulate observed monthly rainfall in India (Upper Godavari River basin) from 1961 to 2005. The results showed that the best models were MPI-ESM-P, MPI-ESMLR, and CNRM-CM5-2 from the CP method and NorESM1-M, FIO-ESM, and MPI-ESM-LR from the GPI technique. In this study, the GCM of Germany, MPI-ESM-LR (m4), was also the second-best model for simulating the monthly rainfall of Amhara, Ethiopia. Using high-resolution (0.22^0) CORDEX for Africa data for the RCP 8.5 scenario, Geleta et al. (2022) studied projections of future climate change trends for near- (2030s), mid- (2050s), and long-term (2080s) periods, in four towns located in southwest Ethiopia. They found that most models projected declining future precipitation compared to the base period (1971–2005). According to their study, there will be a significant change in future temperature patterns, but no significant changes in precipitation were identified. Compared to the climatological base period (1981-2020), the result of our study shows an increase in annual rainfall amount for the three RCPs and the three future periods except for RCP8.5 in the long-term period (2081-2100). Hailesilassie et al. (2022) applied the Long Ashton Research Station Weather Generator (LARS-WG) model for precipitation projection based on five GCMs (MIROC-ESM, HadGEM2-ES, EC-EARTH, INM-CM4, and CCSM4) from CMIP5 under RCP4.5 and RCP8.5 for 2041–2060 compared to 1976–2005 baseline period in Central Ethiopia Main Rift area. The result showed that summer precipitation (often the rainy season) was predicted to fall while winter precipitation (often the dry season) was expected to climb in both scenarios; also, annual and spring precipitation was anticipated to decrease in most locations (Hailesilassie *et al.*, 2022). In this study, Amhara's projected monthly and annual mean rainfall amount will be higher than that of the historical for all RCPs except for RCP 8.5 in the long-term future (2081-2100).

Vegetation mediates the exchange of moisture, energy, trace gases, and aerosols between the

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

atmosphere and land or earth's surface. According to Spracklen *et al*. (2018), deforestation of tropical forests leads to reduced surface roughness and evapotranspiration, increasing air temperature and impacting boundary layer circulations, which increase rainfall over some regions while decreasing it elsewhere. They found that regional rainfall is reduced by up to 40% due to reduced moisture recycling caused by large-scale deforestation. Although the impacts of tropical land-cover change on rainfall are uncertain, they could be of similar magnitude to the impacts of climate change (Spracklen *et al*., 2018). This study did not investigate the relation between rainfall amount and distribution and vegetation cover change.

Recently, Van Vooren et al. (2019) and Kassahun et al. (2023) evaluated the performance of CORDEX-Africa in simulating the climate of the northern part of Ethiopia. The main focus of the first study was on the sensitivity of the models' representation to orography in the northern part of Ethiopia using data from 12 rain gauges (from two and ten sites in the Amhara and Tigray regional states of Ethiopia, respectively) from October 1992 to September 2006. Whereas the main focus of the second study was on evaluating the performance of the CORDEX-Africa regional climate models using a total of five stations' data in the border between Amhara and Tigray regional states of Ethiopia from 1984-2018. In contrast to the above recent studies, the main focus of our study was on evaluating the performance of reliable CORDEX global circulation models (GCMs) that have been used for projecting rainfall using observation and satellite merged grid data for 71 sites/grids that can represent the whole Amhara regional state of Ethiopia from 1981 to 2020. Thus, the result of our study will have more practical applications for projecting rainfall in Amhara.

CONCLUSION AND SUMMARY

In this study, CORDEX data were used to screen, test, and validate reliable Global Circulation Models (GCMs) and to analyze future rainfall projections across Amhara, Ethiopia, in the near-term (2021–2040), mid-term (2041-2060), and long-term (2081-2100) periods. For comparison with future scenarios, observed rainfall data from 1981 to 2020 were selected as the baseline year. The test and validation results were satisfactory from 1981 to 2005 and from 2006 to 2020, respectively. Instead of considering only political boundaries, such as regional states or districts, considering climate boundaries or regions will make climate analyses more relevant because climate has no boundaries. Thus, in this study, the study area was divided into rainfall regimes to consider climate divisions or sub-divisions. Accordingly, *Figure 2* precisely represents the five rainfall shape regimes of the Amhara regional state of Ethiopia, which can be a valuable reference for other related studies.

For projecting the future rainfall of Amhara, five GCMs were selected or screened based on the availability and reliability of historical and future data. Then, the five GCMs were compared with observation data. The test and validation results showed that the UK (HadGEM2-ES) and Germany (MPI-ESM-LR) GCMs were best at simulating the monthly rainfall of Amhara. Because CORDEX data had a large discrepancy in historical and projected rainfall, three non-parametric quartile mapping methods such as 1) robust empirical quartiles, 2) empirical quartiles, and 3) smoothing splines, were compared in correcting model biases. The robust empirical quartiles method was the best bias correction method in this study. Because taking an ensemble or average of more reliable models is preferred to taking a single model, an ensemble of the UK (HadGEM2-ES) and Germany (MPI-ESM-LR) bias-corrected GCMs was taken for further analyses. In drought-prone areas such as regime A6, the projection of less rainfall amount in the small rainy season or Belg (Feb-May) and higher rainfall amount in the dry season or Bega (Oct-Jan) as compared to the climatological normal will harm agriculture, forestry, and other practices. This shows the need for a more comprehensive and detailed investigation for precise projection of the climate of Amhara, including impact assessment.

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

This study is the first necessary step for the projection of future climate, which not only involves multi-model evaluation and future rainfall projection processes but also helps to understand, contextualize, and use the projection results. Indeed, the ability of models to correctly and accurately simulate future climate may not be diagnosed purely by considering historical simulations, but it can be a good baseline for examining the behavior of models. A fundamental part of developing modeling tools is correcting, quantifying, and explaining model biases and uncertainties and mapping connections between regional climates. Following such and other similar approaches is crucial for building better and sustainable adaption and mitigation capacity. This study was based on a monthly, seasonal, and annual basis. However, the method and concept used in this study can also be used on a ten-day basis, and it can also be applied to any place in the world. Because rainfall and vegetation have a strong relationship, sustainable development policies of different sectors such as climate, agriculture, forestry, and water resources must seriously consider the impacts of vegetation (forest) cover change on regional and local rainfall.

Generally, climate projections resulting from GHG emissions and concentration-based scenarios are essential to know possible climate change adaptation and mitigation options and to minimize the negative impacts of climate variability and change on society and development. They are necessary to investigate possible climate changes and evaluate the opportunities and risks. Thus, they help plan and develop adaptation measures worldwide for different sectors.

ACKNOWLEDGMENTS

The authors thank the Ethiopia Meteorology Institute (EMI), also called the National Meteorology Agency of Ethiopia, and the CORDEX project for providing or allowing access to long years of climate data. The authors thank Dr. Zenebe Mekonnen (senior researcher) and Dr. Adefires Worku (researcher and National Coordinator and Focal Person for the Green Legacy Initiative and the Pan African Great Green Wall) for creating and or supervising the mega project in which this article was a part. The authors also thank the anonymous reviewers. The Ethiopian Forestry Development, which was previously called the Ethiopia Environment and Forest Research Institute, is also acknowledged.

Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability Statement

The dataset used in this study can be found from third parties such as Ethiopia Meteorology Institute, formerly called the National Meteorology Agency of Ethiopia (http://www.ethiomet.gov.et/), and other climate dataset website URLs listed in the main manuscript document.

REFERENCES

Abbass, K., Qasim, M. Z., Song, H., Murshed, M., Mahmood, H., & Younis, I. (2022). A review of the global climate change impacts, adaptation, and sustainable mitigation measures. *Environmental Science and Pollution Research*, *29*(28), 42539–42559. https://doi.org/10.1007/s11356-022-19718-6

African Climate Policy Centre (ACPC). (2018). *Climate for Development in Africa (ClimDev-Africa) Final Report 17 December 2015 – 30 June 2018 RAF-14/0079* (Issue June).

African Climate Policy Centre (ACPC) Policy Brief 6. (2013). Climate Change and Agriculture in Africa: Challenges and Promises. In *ClimDev-Africa (https://www.climdev-africa.org/)*. https://doi.org/10.4324/9781849770767

Akinsanola, A. A., Ogunjobi, K. O., Gbode, I. E., & Ajayi, V. O. (2015). Assessing the Capabilities of Three Regional Climate Models over CORDEX Africa in Simulating West African Summer Monsoon

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

Precipitation. *Advances in Meteorology*, *2015*. https://doi.org/10.1155/2015/935431

Alaminie, A. A., Tilahun, S. A., Legesse, S. A., Zimale, F. A., Tarkegn, G. B., & Jury, M. R. (2021). Evaluation of past and future climate trends under CMIP6 scenarios for the UBNB (Abay), Ethiopia. *Water (Switzerland)*, *13*(15). https://doi.org/10.3390/w13152110

Alemayehu, A., & Bewket, W. (2017). Smallholder farmers' coping and adaptation strategies to climate change and variability in the central highlands of Ethiopia. *Local Environment*, *22*(7), 825–839. https://doi.org/10.1080/13549839.2017.1290058

Ayalew, D., Tesfaye, K., Mamo, G., Yitaferu, B., & Bayu, W. (2012). Outlook of future climate in northwestern Ethiopia. *Agricultural Sciences*, *03*(04), 608–624. https://doi.org/10.4236/as.2012.34074

Ayalew, D. W., Asefa, T., Moges, M. A., & Leyew, S. M. (2022). Evaluating the potential impact of climate change on the hydrology of Ribb catchment, Lake Tana Basin, Ethiopia. *Journal of Water and Climate Change*, *13*(1), 190–205. https://doi.org/10.2166/wcc.2021.049

Bekele-Biratu, E., Thiaw, W. M., & Korecha, D. (2018). Sub-seasonal variability of the Belg rains in Ethiopia. *International Journal of Climatology*, *38*(7), 2940–2953. https://doi.org/10.1002/joc.5474

Belete Berhanu, Yilma Seleshi, S. S. D. and A. M. M. (2016). Bias correction and characterization of climate forecast system re-analysis.pdf. *Royal Meteorological Society*, *23*, 230–243. https://doi.org/DOI: 10.1002/met.1549

Berhanu, B., Seleshi, Y., Demisse, S. S., & Melesse, A. M. (2016). *Bias correction and characterization of climate forecast system re-analysis daily precipitation in Ethiopia using fuzzy overlay*. *243*(March), 230–243. https://doi.org/10.1002/met.1549

Birara, H., Pandey, R. P., & Mishra, S. K. (2018). Trend and variability analysis of rainfall and temperature in the tana basin region, Ethiopia. *Journal of Water and Climate Change*, *9*(3), 555–569. https://doi.org/10.2166/wcc.2018.080

Cheung, W. H., Senay, G. B., & Singh, A. (2008). Trends and spatial distribution of annual and seasonal rainfall in Ethiopia. *International Journal of Climatology*, *28*(13), 1723–1734. https://doi.org/10.1002/joc.1623

Clarke, B., Otto, F., Stuart-Smith, R., & Harrington, L. (2022). Extreme weather impacts of climate change: an attribution perspective. *Environmental Research: Climate*, *1*(1), 012001. https://doi.org/10.1088/2752-5295/ac6e7d

CSA. (2007). *The 2007 Population and Housing Census of Ethiopia: Federal Democratic Republic of Ethiopia Population Census Commission*. 1–125.

Deepthi, B., & Sivakumar, B. (2021). Performance assessment of general circulation models : application of compromise programming method and global performance indicator technique Performance assessment of general circulation models. *Stochastic Environmental Research and Risk Assessment*. https://doi.org/10.1007/s00477-021-02124-8

Demaeyer, J., Penny, S. G., & Vannitsem, S. (2022). Identifying Efficient Ensemble Perturbations for Initializing Subseasonal-To-Seasonal Prediction. *Journal of Advances in Modeling Earth Systems*, *14*(5). https://doi.org/10.1029/2021MS002828

Demissie, T. A., & Sime, C. H. (2021). Assessment of the performance of CORDEX regional climate models in simulating rainfall and air temperature over southwest Ethiopia. *Heliyon*, *7*(8), e07791. https://doi.org/10.1016/j.heliyon.2021.e07791

Diro, G. T., Toniazzo, T., & Shaffrey, L. (2011). *African Climate and Climate Change*.

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

43(February). https://doi.org/10.1007/978-90-481-3842-5

Dosio, A., Lennard, C., & Spinoni, J. (2022). Projections of indices of daily temperature and precipitation based on bias-adjusted CORDEX-Africa regional climate model simulations. *Climatic Change*, *170*(1–2), 1–24. https://doi.org/10.1007/s10584-022-03307-0

EPCC. (2015). Ethiopian panel on Climate Change (2015), First Assessment Report, Working Group I Report on climate change on Ethiopia. In *Physical Science Basis* (Issue August). https://www.researchgate.net/publication/282878295_Ethiopian_panel_on_Climate_Change_2015_First_Assessment_Report_Working_Group_I_Physical_Science_Basis_Published_by_the_Ethiopian_Academy_of_Sciences

Geleta, T. D., Dadi, D. K., Funk, C., Garedew, W., Eyelade, D., & Worku, A. (2022). Downscaled Climate Change Projections in Urban Centers of Southwest Ethiopia Using CORDEX Africa Simulations. *Climate*, *10*(10). https://doi.org/10.3390/cli10100158

Gisila, Tesfaye; Seid, Jemal; Shemelis, Andualem; Gebremariam, Temesgen; Jember, Gebru; Amsalu, A. (2015). *Ethiopian panel on Climate Change, First Assessment Report, - Working Group II Water and Energy, Published by the Ethiopian Academy of Sciences* (S. Mengistu, Gizaw; Mengitou (ed.); Issue August).

Grose, M. R., Narsey, S., Trancoso, R., Mackallah, C., Delage, F., Dowdy, A., Di Virgilio, G., Watterson, I., Dobrohotoff, P., Rashid, H. A., Rauniyar, S., Henley, B., Thatcher, M., Syktus, J., Abramowitz, G., Evans, J. P., Su, C. H., & Takbash, A. (2023). A CMIP6-based multi-model downscaling ensemble to underpin climate change services in Australia. *Climate Services*, *30*(August 2022). https://doi.org/10.1016/j.cliser.2023.100368

Hailesilassie, W. T., Goel, N. K., Ayenew, T., & Tekleab, S. (2022). Future precipitation changes in the Central Ethiopian Main Rift under CMIP5 GCMs. *Journal of Water and Climate Change*, *13*(4), 1830–1841. https://doi.org/10.2166/wcc.2022.440

Harris, I., Osborn, T. J., Jones, P., & Lister, D. (2020). Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific Data*, *7*(1), 1–19. https://doi.org/10.1038/s41597-020-0453-3

Herger, N., Abramowitz, G., Knutti, R., Angélil, O., Lehmann, K., & Sanderson, B. M. (2018). Selecting a climate model subset to optimise key ensemble properties. *Earth System Dynamics*, *9*(1), 135–151. https://doi.org/10.5194/esd-9-135-2018

IPCC. (2019). Climate Change and Land: an IPCC special report. *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*, 1–864. https://www.ipcc.ch/srccl/

Kassahun, M., Ture, K., & Nedaw, D. (2023). Evaluation of CORDEX Africa regional climate models performance in simulating climatology of Zarima sub - basin northwestern Ethiopia. *Environmental Systems Research*. https://doi.org/10.1186/s40068-023-00325-4

Kebede, A., & A., M. B. D. and S. (2013). Earth Science & Climatic Change An Assessment of Temperature and Precipitation Change Projections using a Regional and a Global Climate Model for the Baro-Akobo Basin ,. *Earth Science & Climate Change*, *4*(1). https://doi.org/10.4172/2157-7617.1000133

Lee, J.-Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J., Engelbrecht, F., Fischer, E., Fyfe, J., Jones, C., Maycock, A., Mutemi, J., Ndiaye, O., Panickal, S., & Zhou:, T. (2021). Future global climate: scenario-based

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

projections and near-term information. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://doi.org/10.1017/9781009157896.006.553

Lemi, T. (2019). Effects of Climate Change Variability on Agricultural Productivity. *International Journal of Environmental Sciences & Natural Resources*, *17*(1). https://doi.org/10.19080/ijesnr.2019.17.555953

Li, J., Huo, R., Chen, H., Zhao, Y., & Zhao, T. (2021). Comparative Assessment and Future Prediction Using CMIP6 and CMIP5 for Annual Precipitation and Extreme Precipitation Simulation. *Frontiers in Earth Science*, *9*(June), 1–20. https://doi.org/10.3389/feart.2021.687976

Martel, J. L., Brissette, F., Troin, M., Arsenault, R., Chen, J., Su, T., & Lucas-Picher, P. (2022). CMIP5 and CMIP6 Model Projection Comparison for Hydrological Impacts Over North America. *Geophysical Research Letters*, *49*(15). https://doi.org/10.1029/2022GL098364

Mera, G. A. (2018). Drought and its impacts in Ethiopia. *Weather and Climate Extremes*, *22*(June), 24–35. https://doi.org/10.1016/j.wace.2018.10.002

Michael, et al. (2009). Making forests fit for climate change. In *intErnational Union oF ForEst rEsEarch orGanizations*. https://www.fornis.net/sites/default/files/documents/african-policy-brief-en_0.pdf

Moriasi, D. N., Arnold, G. J., Van Liew, M. W., Bingner, R.L., Harmel, R. D., and Veith, T. L. (2007). “Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulation.” *American Society of Agricultural and Biological Engineers, 50*(3), 885−900.

Mutayoba, E., & Kashaigili, J. J. (2017). Evaluation for the Performance of the CORDEX Regional Climate Models in Simulating Rainfall Characteristics over Mbarali River Catchment in the Rufiji Basin, Tanzania. *Journal of Geoscience and Environment Protection*, *05*(04), 139–151. https://doi.org/10.4236/gep.2017.54011

Navarro-racines, C., Tarapues, J., Thornton, P., Jarvis, A., & Ra, J. (2020). *CMIP5 projections for climate change impact assessments*. 1–14. https://doi.org/10.1038/s41597-019-0343-8

NMA. (2007). Climate change national adaptation programme of action (NAPA) of ethiopia Editor: Abebe Tadege This. *Water (Switzerland)*, *2*(June), 73pp. https://doi.org/10.1016/j.cliser.2019.100134%0Ahttp://dx.doi.org/10.1016/j.sbspro.2010.05.169%0Ahttp://dx.doi.org/10.1080/23311932.2015.1134380%0Apapers2://publication/uuid/A172B730-6A69-45C8-8D12-88869ED1E5B8

Ogega, O. M., & Gyampoh, B. A. (2020). Intraseasonal Precipitation Variability over West Scenarios : Results from CORDEX RCMs. *Climate*, *8*(143), 1–20.

Ogega, O. M., Gyampoh, B. A., & Mistry, M. N. (2020). Intraseasonal precipitation variability over West Africa under 1.5 °c and 2.0 °c global warming scenarios: Results from cordex RCMS. *Climate*, *8*(12), 1–19. https://doi.org/10.3390/cli8120143

Seleshi, Y., & Zanke, U. (2004). Recent changes in rainfall and rainy days in Ethiopia. *International Journal of Climatology*, *24*(8), 973–983. https://doi.org/10.1002/joc.1052

Shiferaw, A. S., Ahmed, J. S., Gebremariam, T., & Amsalu, A. (2015). *Ethiopian panel on Climate Change (2015), First Assessment Report, Working Group I Physical Science Basis, Published by the Ethiopian Academy of Sciences* (Issue October).

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

Sisay, K., Vienna, L. S., Thurnher, C., Vienna, L. S., Hasenauer, H., & Vienna, L. S. (2016). Daily climate data for the Amhara region in Northwestern. *INTERNATIONAL JOURNAL OF CLIMATOLOGY*. https://doi.org/10.1002/joc.4880

Spracklen, D. V., Baker, J. C. A., Garcia-Carreras, L., & Marsham, J. H. (2018). The effects of tropical vegetation on rainfall. *Annual Review of Environment and Resources*, *43*(July), 193–218. https://doi.org/10.1146/annurev-environ-102017-030136

Tamoffo, A. T., Nikulin, G., Vondou, D. A., Dosio, A., Nouayou, R., Wu, M., & Igri, P. M. (2021). *Process - based assessment of the impact of reduced turbulent mixing on Congo Basin precipitation in the RCA4 Regional Climate Model*. *0123456789*, 1951–1965.

Tang, C., Morel, B., Wild, M., Pohl, B., Abiodun, B., & Bessafi, M. (2019). Numerical simulation of surface solar radiation over Southern Africa. Part 1: Evaluation of regional and global climate models. *Climate Dynamics*, *52*(1–2), 457–477. https://doi.org/10.1007/s00382-018-4143-1

UNECA. (2011). *Climate Science , Information , and Services in Africa : Status , Gaps and Policy Implications United Nations Economic Commission for Africa*. 1–4.

UNICEF. (2018). Budget Brief Amhara Regional State 2007/08 – 2015/16. *Unicef*, 1–16.

United Nations OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS (UNOCHA). (2018). *Annual Report*. *December*, 1–168.

Van Vooren, S., Van Schaeybroeck, B., Nyssen, J., Van Ginderachter, M., & Termonia, P. (2019). Evaluation of CORDEX rainfall in northwest Ethiopia: Sensitivity to the model representation of the orography. *International Journal of Climatology*, *39*(5), 2569–2586. https://doi.org/10.1002/joc.5971

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

APPENDICES

Appendix 1: Monthly, Seasonal (Bega or Oct-Jan, Belg or Feb-May, Kiremt or Jun-Sep) & Annual historical (1981-2020) and ensembles of m3 & m4 in three RCPs generated future mean rainfall amount [mm] in Amhara and its Rainfall Regimes

Time	A3	A4	A5U	A5L	A6	Amhara	A3	A4	A5U	A5L	A6	Amhara
1981-2020 (climatology or mean)							**2021-2040 (RCP 8.5 mean)**					
Jan	5.5	1.6	0.7	9	7	4.4	14.5	7.4	3.4	14.2	24.5	11.6
Feb	6.9	2.8	1.2	14	9.1	6.5	16	9	3.7	11.4	10.4	8.9
Mar	26	13.7	6.5	43.7	26.9	22.2	37.9	21.8	10.7	21.9	14.6	18.7
Apr	41.4	27.3	14.8	54.3	34.1	32.7	72.7	44.7	31.7	39.5	36.3	40.4
May	127.5	90.8	63.2	45.1	32.4	64.4	105.5	79.1	61.1	36	28.1	56.5
Jun	225.4	176.6	148.6	49.3	33.1	115.8	226.1	168.6	149.8	61.5	40.1	118.4
Jul	352.9	320.1	281	265.5	197.6	276.4	388.1	304.5	274.7	236	161.4	259.8
Aug	352.4	304.7	287.2	270.7	217.2	279.2	402.9	338.5	319.9	286.3	209.8	302
Sep	236.7	177.2	143	87.4	61.4	129.5	270.5	242.4	215.1	160.5	128.2	196.5
Oct	103.8	69.2	41.8	22.8	13.5	43	67.2	37.4	17.9	24.6	20.8	28.2
Nov	25.2	13.8	6.1	11.9	10.1	11.4	20.1	11.8	3.9	22.5	22.9	14.9
Dec	10.6	3.3	1.3	7	6.1	4.7	18.5	10.9	6	17.3	24.6	14.2
Bega	145.1	87.9	49.8	50.7	36.8	63.5	120.2	67.6	31.3	78.6	92.8	68.8
Belg	201.8	134.6	85.6	157.2	102.6	125.8	232.1	154.6	107.2	108.9	89.4	124.5
Kiremt	1167	978.7	859.7	672.8	509.3	801	1288	1054	959.4	744.2	539.6	876.8
Annual	1514	1201	995.2	880.6	648.7	990.2	1640	1276	1098	931.7	721.7	1070.1
			2021-2040 (RCP 4.5 mean)						**2021-2040 (RCP 2.6 mean)**			
Jan	8.4	5.8	2.4	12.8	19.3	9.2	11.9	6.1	2.8	12.6	18.7	9.5
Feb	17.9	10.5	3.8	10.9	7.7	8.8	17.4	10.3	4.6	15.4	15.6	11.5
Mar	33.4	17.8	8.9	16.4	12	15.1	40.2	22.3	12.2	22.1	16.1	19.7
Apr	83.9	55.1	38.9	45.6	37.9	47.4	76.2	49	34.3	43.1	36.3	43.2
May	108.5	84.4	68.7	49.6	41.6	65.7	103.5	79.6	60.5	44.6	35	59.6
Jun	228.4	169.8	147.7	64.7	38.4	118.8	216.4	154.6	132.5	57.4	35.7	108
Jul	378.8	299.4	264.6	240.8	159.2	256	360.7	282.7	246.8	228.5	145	240.4
Aug	372.1	322.5	320	266.1	211.5	291.5	391.2	338.6	323.4	286.3	212	302.5
Sep	250.5	217.8	184.1	149.4	104.6	174	244.5	210.4	183.8	134.2	99.3	167.1
Oct	60.2	39.4	21.4	34	26.8	32.5	73.5	50.2	30.6	42.8	36.7	42.4
Nov	34.1	18.5	8.5	23.4	21.4	18.6	33.6	20	9	29.8	32.2	22.6
Dec	20	11.5	5.1	22.2	29.4	16.2	28.2	13.9	6.3	16.6	24.7	15.5
Bega	122.7	75.3	37.4	92.3	96.9	76.5	147.2	90.2	48.7	101.8	112.4	90
Belg	243.7	167.7	120.3	122.5	99.2	137	237.3	161.3	111.6	125.1	103.1	134
Kiremt	1230	1009	916.4	721	513.8	840.2	1213	986.4	886.4	706.5	492	818

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

Time	A3	A4	A5U	A5L	A6	Amhara	A3	A4	A5U	A5L	A6	Amhara
Annual	1596	1253	1074	935.8	709.9	1053.7	1597	1238	1047	933.4	707.5	1042
2041-2060 (RCP 8.5 mean)							**2041-2060 (RCP 4.5 mean)**					
Jan	8.6	6.3	2.4	15.3	22.1	10.5	3.6	3.4	1.4	11.5	19.1	7.7
Feb	16.4	9.2	4.6	13.3	14.2	10.4	10.2	7.3	3.2	9.6	10	7.5
Mar	37.5	22.2	11.3	23.5	16.1	19.5	38.7	21.4	13.1	18.3	15.1	18.5
Apr	66.3	42.4	30.3	37.7	30.1	37.5	81.7	52	36.7	41.1	28.8	43.1
May	107.7	80.8	63.7	38.4	30.4	58.7	96.1	74.4	59.2	36.2	28.8	54.4
Jun	214.6	155.8	136	56.7	34.1	108.6	219.2	159.7	134.6	63.2	38.4	111.8
Jul	378.6	291.7	256.8	229.3	152.4	248	372.8	291.8	248.5	228	147.2	244.2
Aug	394.8	345	328.1	290.5	214	306.9	408.4	345.6	329.2	285.6	204.8	305.5
Sep	253.5	224.3	202.4	139.1	102.8	177.9	250.7	220.3	189.5	139.6	104.3	173.7
Oct	72.9	46.3	29.4	38.3	30.6	38.9	68.4	45.9	27.2	38.4	33.5	38.4
Nov	31.6	20.2	10	31.5	34.1	23.5	31.2	18.7	8.2	24.9	24.7	19.4
Dec	17.4	9.8	4	18.6	25.4	13.8	26.9	14.5	6.4	22.4	31.7	18.2
Bega	130.5	82.6	45.8	103.7	112.3	86.6	130	82.4	43.3	97.2	109	83.7
Belg	227.9	154.6	109.9	112.9	90.8	126.1	226.8	155.1	112.2	105.2	82.7	123.5
Kiremt	1242	1017	923.3	715.5	503.4	841.5	1251	1018	901.8	716.5	494.6	835.2
Annual	1600	1254	1079	932.1	706.6	1054.2	1608	1255	1057	918.8	686.3	1042.3
2041-2060 (RCP 2.6 mean)							**2081-2100 (RCP 8.5 mean)**					
Jan	6.7	4.3	1.9	13.6	21.4	9.2	15.4	9.6	3.7	15.5	21.8	12.1
Feb	7.5	5.7	1.9	11	9.8	6.8	15.3	10.8	4.3	11.4	10.3	9.4
Mar	29.7	17	10.2	14.4	10.5	14.2	37.6	22	12.6	22.1	15.3	19.4
Apr	75.5	49.7	36.1	43.1	38	44.2	68.8	47.2	32.8	37.7	31.5	39.7
May	98.3	77.3	62.6	41.1	28.6	57.3	73.1	60.2	47.8	30	20.2	43.2
Jun	221.1	159.2	134.1	65.2	40	112.5	182.9	125.2	108.1	43.5	26.7	87.1
Jul	378.9	297.8	260.4	234.8	152.7	251.9	315.9	247.6	206.2	186.4	113.1	202.1
Aug	389.6	343.7	322.7	287.8	210.8	303.6	383.6	331.7	304	294.7	200.9	295.1
Sep	248.6	221.7	188.2	141.9	104.6	174.1	248.2	223.1	197.7	137.8	101.7	175.4
Oct	76.7	46.6	23.1	35.7	29.8	36.7	73.7	52.1	28.6	47.3	39.6	43.9
Nov	27.4	16.1	7.1	20.3	21.4	16.5	38	25.9	13.8	34.9	33.8	27.1
Dec	12	6.3	3	13.9	21.1	10.3	23.5	15.6	8.1	23.2	29.1	18.4
Bega	122.7	73.3	35	83.5	93.7	72.7	150.6	103.1	54.1	120.9	124.2	101.5
Belg	211.1	149.6	110.9	109.6	86.8	122.5	194.7	140.3	97.5	101.1	77.2	111.7
Kiremt	1238	1022	905.4	729.7	508	842	1131	927.6	816	662.4	442.4	759.7
Annual	1572	1245	1051	922.8	688.5	1037.2	1476	1171	967.6	884.5	643.9	972.9
2081-2100 (RCP 4.5 mean)							**2081-2100 (RCP 2.6 mean)**					
Jan	8.5	6.6	2.7	16.3	26.2	11.6	11.9	6.8	3.5	13.9	24.2	11.1

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

Time	A3	A4	A5U	A5L	A6	Amhara	A3	A4	A5U	A5L	A6	Amhara
Feb	12.3	7.6	2.4	8.9	8.4	7	20.2	11.1	4.6	13.5	12.7	10.9
Mar	35.2	21.1	12.7	21.8	17.7	19.4	43.4	26.4	11.9	33.6	23.3	24.8
Apr	68.9	45.4	29.5	36.2	27.9	37.4	88.3	58	44.7	51.2	48.7	53.3
May	91.5	71.3	58.6	34	25.1	51.9	111.5	86.4	72.3	43.9	33.5	64.5
Jun	213.5	151.4	126.9	56	31.5	104.4	206.3	145.3	125.1	49.4	28	99.7
Jul	368.3	289.4	249.2	222.8	143	241.4	385	308	274	235.9	161	260.2
Aug	410.9	352.5	332.3	306.4	219.2	315.7	386.6	339	329.6	283.8	208.7	302.7
Sep	249.6	220.4	189.9	131.3	97.3	170.4	242.8	208.3	175.6	121.2	79.1	157.5
Oct	65.1	40.5	19.3	37.1	31	34	59.9	39.3	20.3	31.8	26	31.5
Nov	29.2	19	9.4	26	25.2	20	28	17.3	6.2	26.3	24.2	18.5
Dec	13.3	8	3.6	17.2	24.5	12.4	14	8.8	5.5	19.9	31.7	15.1
Bega	116.2	74	35.1	96.6	106.9	78	113.7	72.1	35.5	91.9	106.1	76.2
Belg	207.9	145.4	103.1	100.9	79.1	115.7	263.3	181.9	133.5	142.3	118.1	153.5
Kiremt	1242	1014	898.3	716.4	491	832	1221	1001	904.3	690.2	476.8	820.1
Annual	1566	1233	1037	913.8	677.1	1025.7	1598	1255	1073	924.4	701	1049.8

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

Appendix 2: CORDEX Project GCMs Data Downloading and Bia Correction Steps

The website for climate4impact was used to download regional climate model (RCM) data for Africa (AFR-44). For example, the below steps were used to download historical as well as RCP2.6, RCP4.5, & RCP8.5 monthly precipitation data. The below steps can also be used to download other meteorological parameters such as Monthly Maximum and Minimum Near-Surface Air Temperature.

- Register and get user name and password for free data access from the climate4impact website: https://climate4impact.eu/impactportal/data/esgfsearch.jsp#
- Using the above website URL, sign in with CEDA/BADC using Mozilla Firefox web browser and choose the option' Data discovery' just next to 'Home'.
- From 'Filters', choose or select the following options: Project = 'RCM data CORDEX'; Parameter = 'Precip. (pr)'; Frequency = 'monthly'; Experiment = 'Historical', 'Radiative forcing of 2.6, 4.5, and 8.5 Wm^{-2}'; Domain = 'AFR-44'; Driving model = 'ICHEC-EC-EARTH', 'MIROC-MIROC5', 'MOHC-HadGEM2-ES', 'MPI-M-MPI-ESM-LR', 'ICHEC-EC-EARTH'; Ensemble = 'r1i1p1'; Rcm_name = 'RCA4'; in the absence of RCA4 'REMO2009' can be used. Note: r1i1p1.RCA4.v1 is preferred to other RCMs.
- If 'wget' or 'Export to CSV' option does not work, download the individual files. Note that the files (the CORDEX data) is in NetCDF file format.
- After successfully downloading the data, extract the data for the study site using CDO in Ubuntu or Windows subsystem for linux (WSL2) platforms. For example, in this study, the command' cdo sellonlatbox,35.2,40.2,8.7,13.8 file_in.nc file_out .nc' was used in WSL2 platform to extract for Amhara site. Climate Data Tool (CDT version 6.0) package applied in R Statistical software (R version 3.6.1) was also used to merge or aggregate daily values to monthly values, to extract 71 selected grid points and to convert to CSV file format. Equivalently the below R script in R (RStudio) was used to extract values from NetCDF files and save the result to MS-Excel or CSV file format:

library(ncdf4) # calling package ‘ncdf4’ which enables working with NetCDF files

library(raster) # to work with spatial data having values for a given longitude and latitude

nc <- nc_open(file.choose()) # to choose the NetCDF file from a folder

print(nc) # to get variable name

names(nc$var) # shorter way to get variable name

lon <- ncvar_get(nc, "lon")

lat <- ncvar_get(nc, "lat")

#data <- ncvar_get(nc)

#Import and read netcdf as a raster brick

data <- basename(file.choose());data

nc<- brick(data,varname="tasmax")

stations<-read.csv("stations.csv") # to read the Excel or CSV file 'stations' with desired latitude & longitude

data_ext<-t(extract(nc,stations[c(2,3)])) # to extract & transpose for the lists of latitude & longitude points in columns 2 & 3.

data_ext=data.frame(data_ext) # to change to data.frame data format

data_ext=data_ext*86400 # for rainfall data: to change Kg/m^2/s to mm/day (for temperature data: to change Kelvin to oC subtract -273.15 from each values)

library(writexl); library("xlsx") # calling packages which enable writing the output to MS-Excel

write.xlsx (data_ext, "model1.xlsx", row.names = FALSE, sheetName = "1981-2020", append=TRUE) # to write the result to MS-Excel called ‘model1’ in a sheet called ‘1981-2020’

Then, station and satellite merged data was downscaled to CORDEX data grid resolution (0.44^{o} × 0.44^{o}). It was used as a reference to compare the performance of the five climate models (GCMs) and to correct rainfall model data biases using non-parametric quintile mapping (QM) implemented in R software using 'qmap' package in three options: 1) robust empirical quartiles (RQUANT), 2) empirical quartiles (QUANT), and 3) smoothing splines (SSPLIN).

Software used for Data Analysis

The calculations, data analyses, and graphs in this paper were performed using Microsoft Excel worksheet and R statistical software packages. For Network Common Data Form (NetCDF) data analysis, Climate Data Operators (CDO) was used in Windows Subsystem for Linux (WSL2) interface; Ncview

Article DOI: https://doi.org/10.37284/ajccrs.3.1.1730

operator is used in Linux (Ubuntu 20.04 LTS) operating system interface. For grid data analysis, a free, opensource R package, the Climate Data Tool (CDT) which is created specifically for national meteorological services was used. QGIS 3.22.11 and ArcGIS 10.8 were used for spatial interpolating.