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Original Research

Tempospatial Variability and Change in Future Rainfall and Temperature under RCP Scenarios in Didessa River Basin, Ethiopia

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Abstract

Didessa River Basin contributes one-fourth of the Blue Nile's annual total flow. However, climate change and variability information is generally lacking under Representative Concentration Pathways (RCPs) in the study basin. This study was designed to assess future rainfall and temperature variability and change under RCP2.6, 4.5 & 8.5 scenarios in the 2030, 2050, and 2080's of the 21st century with reference to 1984 to 2014 historical rainfall and temperature. Ensemble mean of daily rainfall and temperature data of 17 CMIP5 climate models was collected from MarkSim™ *weather generator in the Google Earth interface. Changes in onset and cessation of rain season between the historical and future periods were assessed using the INSTAT+v3.37 version. Results of the study indicated decrease in the average winter season rainfall amount at three* stations *while that of the remaining three stations increased under all RCP scenarios in all three future time intervals. Autumn season rainfall increases at three stations and decreases at the others under all RCP scenarios. Rainfall CV increases under all RCP scenarios compared to 1984 to 2014 historical rainfall in all future time intervals. The length of the rain season decreases in three future periods under all RCPs while maximum and minimum temperatures increase up to 3.58 °C and 2.7°C, respectively, in the late 21st century under RCP8.5. Therefore, it is important to increase forest cover as a mechanism to increase sink for carbon dioxide and also to select crop varieties, which easily adapt to climate change.*

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INTRODUCTION

Climate variability and change are among the major pressing environmental challenges of the 21st century (Parry et al., 2007) with developing countries particularly affected due to their economic, climatic, and geographic settings and lower adaptive capacity (Mertz *et al.*, 2009). Attributed to climate change, the population at risk of increased water stress in Africa was projected to be between 75-250 and 350-600 million by 2020s and 2050s, respectively, with yield reduction in rainfed agriculture dependent countries by 50% of the current (IPCC 2014, 2022). As a consequence, the achievement of sustainable development in the Horn of Africa is possible by enacting climate risk adaptation and mitigation strategies linked to regional and local climate information (Surendran *et al*., 2014 and Ampaire *et al*., 2015).

According to the National Report of the Federal Democratic Republic of Ethiopia (FDRE, 2022) to The United Nations Convention Framework on Climate Change, the agricultural sector contributes 37% of the country's GDP and about 68% of the total employment. This sector supplies 75 percent of the raw material requirement of agriculture based domestic industries (MoFED, 2010). However, the production system is mainly dependent on natural rainfall conditions, which are highly susceptible to annual and seasonal rainfall changes and variability. Research finding indicates historical occurrences of recurrent droughts due to climate change and variability *(Gissila et al., 2004)*. There had also been occurrences of occasional floods in the country in the years 1993, 1996, 1998, and 2006 coupled with the death of people and resource damage (NMA, 2007).

Previous research reports regarding the model simulated future rainfall in the Horn of Africa in general and Ethiopia, in particular, vary considerably. Gessica *et al*. (2015) reported that the Horn of Africa will have higher rainfall as global temperatures rise compared to that in the 20th century. In the contrary, Mugi (2017) reported that areas around the equator will have a higher drought severity between 2070 and 2100 compared to other areas under RCP4.5 and RCP8.5 based on HadGEM2–AO model simulation. A study report from Amhara National Regional State of Ethiopia indicated a decrease in the amount of annual rainfall in the 2080s (Ayalew *et al*., 2012). Increase in projected winter (main rain season) rainfall by 12 to 69% and a decrease in the autumn (short rain season) rainfall by 20 to 68% was reported from a study in the Rift Valley area of Ethiopia, which employed ECHAM5 general circulation model and an ensemble mean of six models under A2 (high) and B1 (low) emission scenarios in the periods 2020 to 2049 and 2066 to 2095 (Muluneh *et al*., 2015). A decrease in winter season rainy days with probable water logging problem that affects crop production was reported from a study employed CSIRO-Mk3-6-0, Had GEM2-ES and MIROC-ESM-CHEM GCMs in Northeastern Amhara Region of Ethiopia (Muluneh, 2015). The lack of a clear trend in projected monthly precipitation in the coming 2021 to 2050 and 2071 to 2100 was also reported from a study at Lake Tana catchment in Ethiopia stating that some models indicate increasing trends while others show a decreasing trend for a given month (Enyew *et al*., 2014). A study report based on CORDEX Africa RCM Model from Bale highlands indicated that future rainfall change is variable in the early, mid, and late 21st century under RCP4.5 and 8.5 (Legesse, 2017). Another study using CORDEX-Africa RCM Models projection also shows the highest likely occurrence of Extreme events in southwest Ethiopia stations at the end of the twenty-first century (Geleta *et al*., 2022).

With regard to future temperatures, most simulation reports agree on the rise. Mean annual temperatures in East Africa are projected to be on average, 0.6°C, 1.1°C and 2.1°C warmer than the 1994–2005 average, respectively by the early, mid, and late 21st century (Anyah and Qiu, 2012; IPCC, 2012; 2014) and reach up to 6ºC a the end of the century under RCP8.5 (IPCC, 2022). A higher temperature increase in East Africa was also reported for the long rainy season (Ngaina *et al*., 2015). Reports from Bale Highland of Ethiopia also indicated an increase in temperature in the early, mid, and late 21st century indicating a higher increase under RCP8.5 (Legesse, 2017). Another study in Northwestern Ethiopia, which employed CMIP3 SRES scenarios also reported an increase in maximum and minimum temperature from 1.55˚C to 6.07˚C and from 0.11°C - 2.81°C, respectively, in the 2080s *(*Ayalew *et al.,* 2012*)*. With this regard, it is paramount to analyze spatial and temporal variability and changes in future rainfall and temperature in the local context to implement locally suitable climate change and variability adaptation and mitigation measures.

In this specific study, the CMIP5 17 climate model ensemble's mean was selected to predict future rainfall and temperature under RCP scenarios. These Fifth Model Intercomparison Project (CMIP5) climate models incorporated recent observation research included a wider range of future conditions and emissions and have higher spatial resolution compared with the previous SRES scenarios (Sillman *et al*., 2013). The RCP scenarios (RCP2.6, RCP4.5, RCP6, and RCP8.5) imply radiative forcing of 3 W/m^2, 4.5 W/m^2, 6 W/m^2 and 8.5 W/m^2, respectively, in 2100. In contrast to the SRES scenarios, the radiative forcing trajectories in the RCPs are not associated with predefined storylines and reflect various possible combinations of economic, technological, demographic, and policy developments (Moss *et al*., 2010).

Therefore, the main objective of the study was to analyze annual and seasonal changes and variability in future rainfall and temperature using 17 CMIP5 climate model ensemble means under RCP scenarios in the near (2018 - 2043), mid (2044 - 2069), and long term (2070 to 2095) periods compared with the historical rainfall and temperature over 1984 to 2014 in the Didessa River basin.

Materials and Methods

Description of the study area

The study area, the Didessa River basin, is located within the Blue Nile basin between 35º0'0" and 37º0'0" East longitude and 7º30' 0" and 9º60'08" North latitude (Figure 1), and its estimated total area is about 1,930,233 hectares. The river basin includes parts of Eastern and Western Wollega, Jimma, Illu Ababor, Buno Bedele, and Kemash administrative zones. It is characterized by a humid tropical climate with heavy annual rainfall. The mean annual rainfall of the river basin ranges between 1200 mm and 2200 mm. About 3/4 of the total annual rainfall is received during the winter (June to September) rain season. The Autumn (February to May) season contributes about 1/5 of the annual rainfall total. Summer season rainfall contributes the remaining proportion of the total annual rainfall. Based on the temperature data between 1984 and 2014, the mean average maximum and minimum temperature of the river basin range between 21.1 – 36.5ºC and 7.9 – 16.8 ºC, respectively. On the basis of altitude, the river basin encompasses about 81.55%, 18.38%, and 0.08% midland, lowland, and highland, respectively. As indicated by the Ethiopian population and Housing census, there are about 2,992,164 total residents in the sub-basin (CSA, 2008). More than 88 % of the total population are rural residents and agriculture is the dominant economic activity and source of their livelihood.

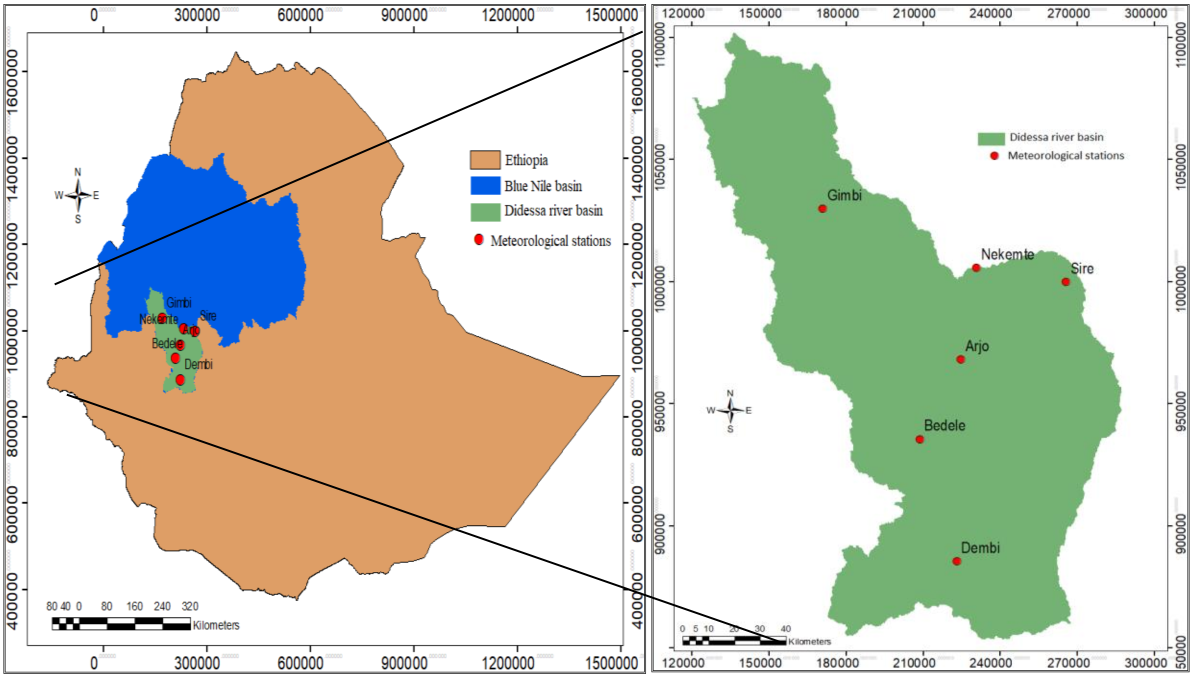

Figure 1: Map of Didessa River Basin

Climate ata sources

Ensembles mean of 17 CMIP5 climate models daily rainfall, maximum and minimum temperature were downloaded from MarkSim^{TM} DSSAT Weather file generator in the Google Earth interface. MarkSim^{TM} DSSAT Weather file generator is a web-based tool that generates downscaled point weather data in the Google Earth interface (Jones and Thornton, 2013). The source was chosen because it provides comparable point data of the climate variables. Six meteorological stations, and latitudinal and longitudinal coordinates (Figure 1) were input to the model. After identification of the exact station point, the RCP scenarios, and GCMs of interest, the model generated daily data of rainfall and temperature for the years from 2018 to 2095. Daily rainfall amount, mean maximum, and minimum temperature data as predicted by seventeen climate model ensembles (Bcc-csm1, Bcc-csm1-1-m, Csiro-mk3-6-0, Fio-esm, Gfdl-cm3, Gfd1-esm2g, Gfdl-esm2m, Giss-E2-H, Giss-E2-R, Hadgem2-es, Ipsl-cm5a-lr, Ipsl-cm5a-mr, Miroc5, Miroc-esm, Miroc-esm-chem, Mri-cm31 and Noresm1-m) were downloaded at six meteorological stations. The stations (Arjo, Bedele, Dembi, Gimbi, Nekemte, and Sire) are located at 2469, 2030, 1950, 1835, 2124, and 1826 meters above sea level, respectively.

Variability of future rainfall

Rainfall Coefficient of Variation (CV), Precipitation Concentration Index (PCI), and Standardized Rainfall Anomaly were used as indicators of rainfall variability *(Ayalew et al., 2012).*

The rainfall coefficient of variation (CV) is the ratio of the rainfall standard deviation to the mean over a period of time. Annual and seasonal rainfall coefficients of variation for the representative meteorological stations were determined as the ratio of standard deviation to the mean rainfall (Eq.1).

$$CV = \frac{Sd}{X} \qquad (1)$$

Where Sd = Standard deviation; X = annual and seasonal rainfall mean. The rainfall of an area is classified as poorly variable, moderate variable, and high variable when the Coefficient of Variation (CV) is < 20%, 20% to 30%, and > 30%, respectively (NMSA, 1996).

The Precipitation Concentration Index (PCI) is an indicator of monthly rainfall distribution in the rainfall data series. PCI was calculated using (Eq. 2) given by (Oliver, 1980) and later modified by (De Lui's *et al*., 1999).

$$PCI = \left(\frac{\sum_{i=1}^{12}(\mathrm{Pi})^{\wedge}2}{(\sum_{i=1}^{12}\mathrm{Pi})^{\wedge}2}\right) X\ 100 \qquad (2)$$

Where p_i is the total monthly rainfall amount.

The following definitions were used to categorize future rainfall: PCI values below 10 indicate low concentrations while values between 11 and 15 indicate moderate concentrations. PCI values between 16 and 20 indicate a very high concentration of monthly rainfall distribution and PCI greater than 20 indicates strong irregularity *(De Lui's et al., 1999).*

Standardized Rainfall Anomaly (SRA) is the difference between the annual total and long-term average rainfall records divided by the standard deviation (Eq. 3). The SRA index is used to determine dry and wet years in the rainfall record.

$$SRA = \frac{Xi - Xm}{Sd} \qquad (3)$$

Where X_i = annual rainfall total of a particular year; X_m = mean annual rainfall over the period of observation; Sd = standard deviation of annual rainfall over the period of observation. The SAR values were categorized into extremely wet, very wet, moderately wet, near normal, moderately dry, severely dry, and extremely dry (McKee *et al*., 1993).

Onset, cessation, and length of rain season

The determination of rain season onset, cessation, and length is important to reduce crop yield reduction and associated risks in rainfed agriculture because of either the late onset or early cessation of the rain season (Mawuny *et al*., 2011).

The onset of the rain season in Days of the Year (DOY) was defined based on the water balance techniques provided in Instat+v3.36 software. The first occasion with more than 20mm of rainfall in a 2-day period and no dry spell of 10 days or more within the following 30 days was considered as the onset day of the rain season (Stern, 1982).

The cessation of the rain season marks the withdrawal of the rain season. The cessation date of the rain season in DOY was defined as the day when 5 days evaporation reduces 10 mm/m soil water to less than or equal to half of the Potential Evapotranspiration (Tesfaye and Walker, 2004). The length of the rain season was estimated as the difference between cessation and onset of the rain season in days.

All indicators of rainfall variability (rainfall coefficient of variation, precipitation concentration index, standard rainfall anomaly, rainfall onset and cessation, and length of rain season) were calculated both for the historical and future rainfall. The differences and statistical variations were considered separately for all six stations to capture spatial variations in sites with narrow altitudinal differences.

Results and Discussions

Future mean annual and seasonal rainfall changes

The term change hereafter refers to rainfall and temperature changes between future and historical times. Mean annual and seasonal rainfall at high altitudes increases in all future time intervals under all scenarios except in the summer, autumn, and winter seasons at Arjo, Bedele, and Nekemte, respectively, while it decreases at low altitude (Dembi and Sire) under all RCP scenarios in all three future time intervals except in summer where it increases under all scenarios and all future time intervals. Annual and seasonal rainfall amounts under historical and future periods can be referred from separate appendices Tables 1& 2.

Mean average future annual rainfall totals under RCP scenarios increase at Arjo, Bedele, Nekemte, and Gimbi in the early (2018 to 2043), mid (2044 to 2069), and late (2070 to 2095) 21st century under RCP2.6 while it decreases at Dembi and Sire stations under this scenario in all time intervals. In the following sections, the term time intervals may be used to denote the early, mid, and late 21st century. The mean average annual rainfall also increases under RCP4.5 at Arjo, Bedele, Nekemte, and Gimbi stations while it decreases at Dembi and Sire stations. A further look at mean annual rainfall under RCP8.5 shows an increase at Arjo, Bedele, Nekemte, and Gimbi in all time intervals. The increase in annual mean average rainfall is greater under RCP8.5 than under RCP2.6 and RCP4.5. Mean average annual rainfall amounts at Dembi and Sire stations also showed a decrease under this concentration pathway in the early and mid-century (Figures 2 & 3). Dembi and Sire stations are located at lower altitudes than the remaining stations. Therefore, it can be concluded that the mean average annual rainfall increases at higher altitudes and decreases at lower altitudes.

The winter season contributes more than 64% of the mean average total annual historical rainfall in the river basin. In this season, the highest amount was received by Nekemte and the least from Sire. Winter (June to September) season means average rainfall shows an increase at Arjo, Bedele, and Gimbi in all future time intervals. On the other hand, a decrease in future rainfall was predicted at Nekemte, Dembi, and Sire stations under all RCP scenarios in all time intervals. Here, the segregation of the mean annual total rainfall into mean seasonal rainfall total indicated a decrease in winter season rainfall at Nekemte, while that of others showed a similar pattern to that under the annual time scale (Figures 2 & 3).This finding is contrary to the reports by Geleta *et al*. (2022) who reported declining future precipitation for stations with increasing rainfall and in agreement for stations with predicted decremental trends. However, the number of models used and the historical rainfall length differ considerably. Similarly, the stations are also different except for Bedele.

Regarding the autumn (February to May) season, it contributes about 17% to 22.8% of the mean total historical rainfall in the river basin. This season means annual rainfall increases at Arjo, Nekemte, and Gimbi under all RCP scenarios in all future time intervals. Contrary to this, mean autumn season rainfall decreases at Bedele, Dembi, and Sire stations under all the time intervals and RCP scenarios except at Bedele in the time interval 2070 to 2095 under RCP4.5 and RCP8.5 (Figure 2 & 3). These three stations are located in relatively lower altitude areas compared with the other three. This season is important to land preparation for crop growing and to rejuvenate grass dried in the dry summer season. In agreement with our findings at Bedele, Dembi, and Sire stations, a decrease in autumn season rainfall by 5-6% in the 2080s was also reported from Ethiopia (Amdt *et al*., 2011).

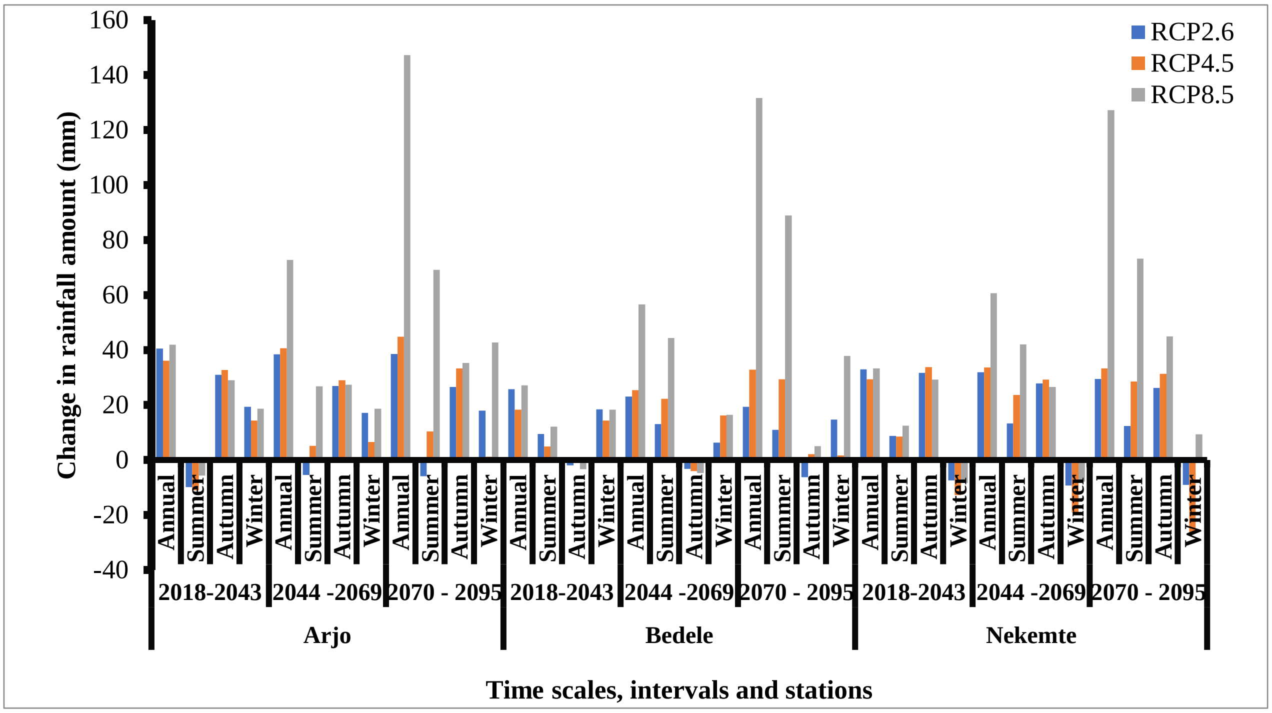

Figure 2: Mean seasonal and annual rainfall change in the three future periods at Arjo, Bedele, and Nekemte stations

Note: *Summer (October to January); Autumn (February to May) and Winter (June to September)*

Summer (October to January) season is the driest of all seasons in Ethiopia in general and the Didessa river basin in particular. This season contributes about 8.9% to 12.9% of the historical mean total annual rainfall in the Didessa River basin. Rainfall in the first two months (October and November) is of particular importance for late-grown crop grain development. Mean annual rainfall of this season increases at Bedele, Nekemte, Dembi, and Sire stations in all time intervals under all RCP scenarios. Here it can be realized that a relatively drier summer season rainfall increases in most stations indicates the existence of temporal change in rainfall in the future time (Figures 2 & 3).

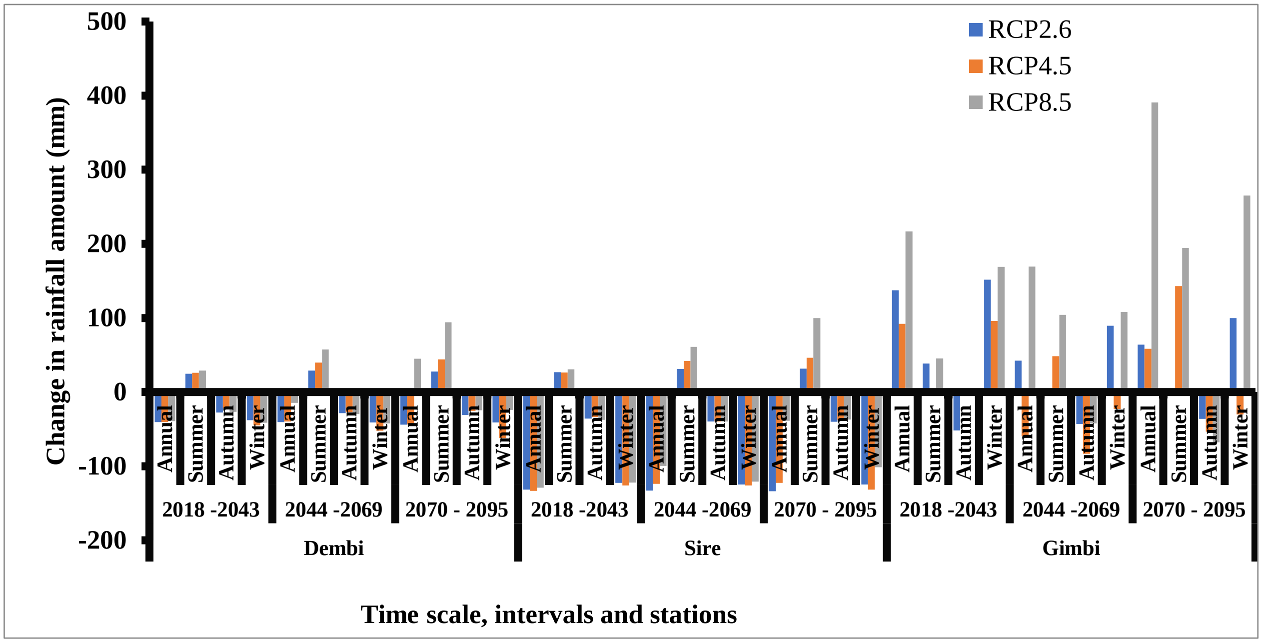

Figure 3: Mean seasonal and annual rainfall change in the three future periods at Dembi, Sire, and Gimbi stations

Rainfall coefficients of variation, concentration indices and anomalies under historical and future periods

Coefficient of Variation

In the following paragraphs, rainfall variability indicators such as Coefficient of Variation (CV), Precipitation Concentration Index (PCI), and Standardized Rainfall Anomaly (SRA) were compared between historical and future rainfall in annual and seasonal time scales. Historical rainfall CV at Arjo, Bedele, Nekemte, and Sire stations indicated low variability (CV < 0.2). Historical rainfall at Dembi was highly variable (CV > 0.3%) while that of Gimbi station was moderately variable with CV between 0.2% and 0.3%. Annual rainfall under RCP2.6 is highly variable at Arjo, Bedele, and Nekemte in the time interval 2070 to 2095 and moderately variable under RCP4.5 in the early and late 21st century.

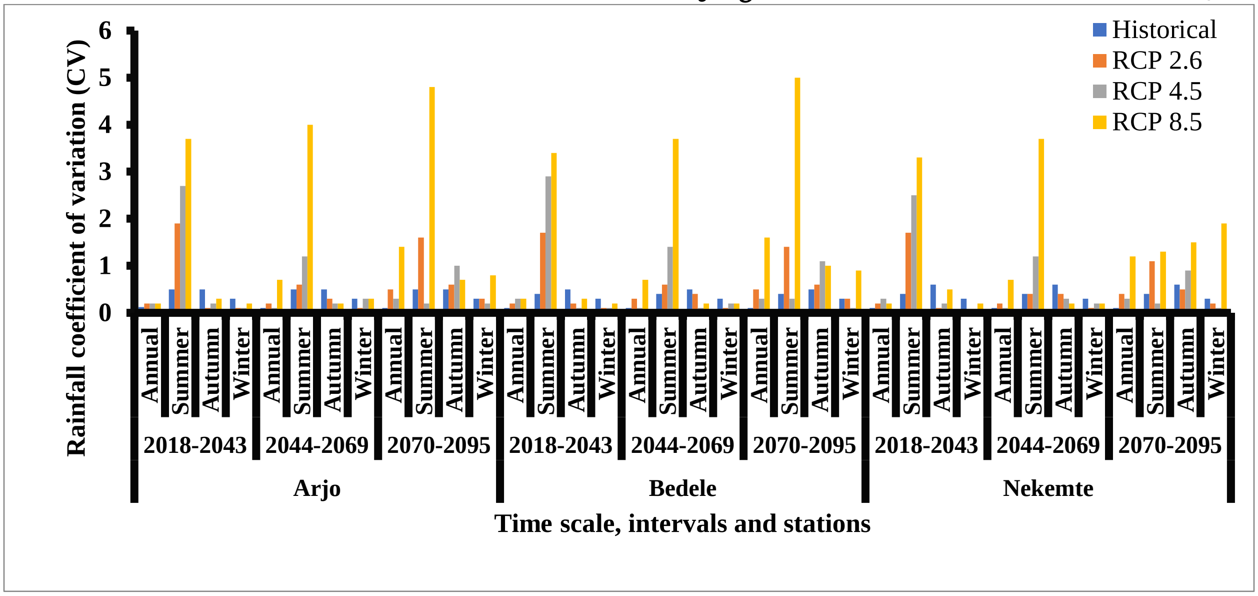

Figure 4: Seasonal and annual future rainfall CV at Arjo, Bedele, and Nekemte stations

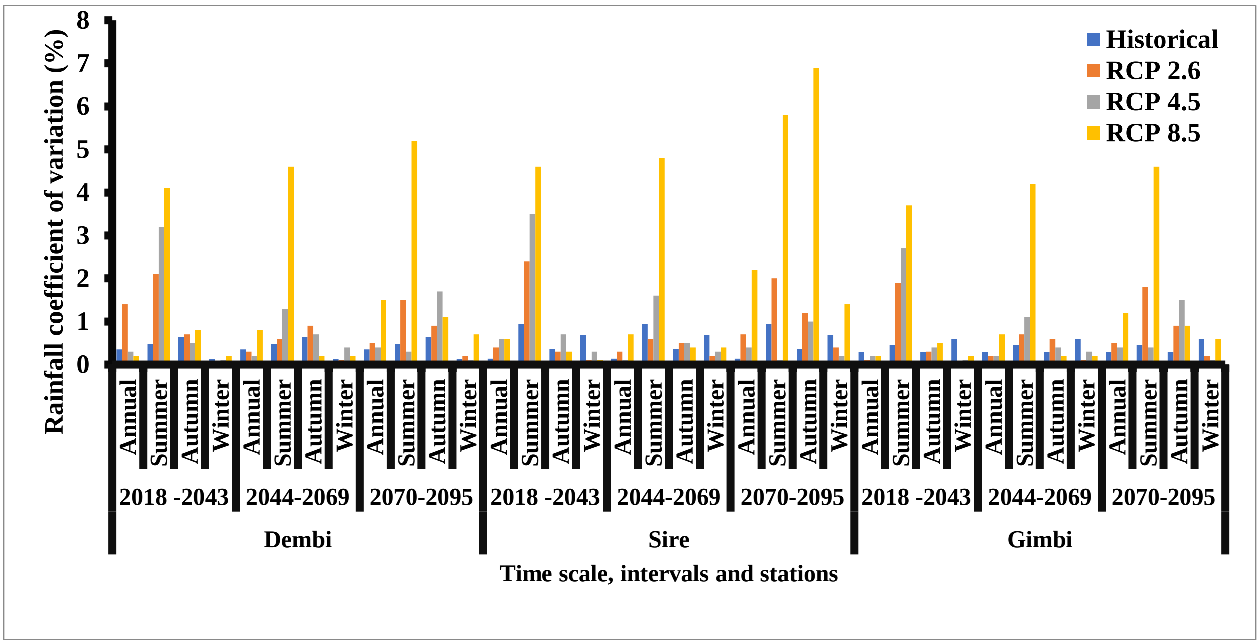

Figure 5: Seasonal and annual future rainfall CV at Dembi, Sire, and Gimbi stations

A further look at the annual rainfall CV under RCP8.5 reveals moderately variable rainfall in the early 21st century and highly variable rainfall in the mid and late 21st century. Rainfall at Dembi, Sire, and Gimbi stations was found to be highly variable under RCP8.5 in the mid and late 21st (Figure 4 & 5).

Winter season historical rainfall was highly variable (CV > 0.3%) at Sire and Gimbi stations while it was moderately variable at Arjo, Bedele, and Nekemte with CV values between 0.2% and 0.3%. This reveals that the rainfall CV at lower elevations was higher than it was under higher elevations. Coming to the scenario-based winter season future rainfall, highly variable CV was found at Arjo, Bedele, Nekemte, and Gimbi stations under RCP8.5 in the late 21st century. Dembi station has highly variable rainfall in the mid and late 21st century under RCP4.5 and RCP8.5, respectively. Sire stations can also have highly variable rainfall under RCP8.5 in the mid and late 21st century (Figure 4 & 5).

Autumn season historical rainfall was highly variable (CV > 0.3%) at all stations. This season of rainfall is highly variable at Arjo, Bedele and Nekemte stations in the late 21st century under all RCP scenarios. Rainfall at Sire and Dembi is also highly variable in the early and mid-21st century under RCP8.5. Gimbi has also highly variable rainfall except in the early and mid-21st century under RCP2.6 and RCP8.5 (Figure 4 & 5).

Summer season historical rainfall was highly variable at all stations. Scenario-based summer season rainfall also exhibits highly variable rainfall under RCP2.6 and RCP8.5 in all future time intervals. The rainfall coefficient of variation generally increases under RCP2.6 and RCP8.5 concentration pathways under all the time intervals (Figure 4 & 5).

A study report indicated that annual and seasonal historical rainfall in Ethiopia is highly variable with CV values ranging between 0.10 and 0.50 (Seleshi and Zanke 2004). Another study report of rainfall CV overall in Ethiopia based on 109 ground-based meteorological stations indicated a rainfall CV above 42% for 17 stations (Addisu *et al*., 2015). This indicates that this study result is within the boundary of rainfall CV reported at the country level. Highly variable rainfall with a CV of 0.31 for the autumn season and less variable rainfall with a CV of 0.12 for the winter season was found at Bale highlands of Ethiopia under RCP4.5 and RCP8.5 scenarios using CORDEX Africa CMIP5 RCM models out of which four are the same with the GCMs used in this study (Enyew *et al*., 2014). This result may not be directly comparable to the current study result in light of the models used and the location of the study area which is in southeastern Ethiopia.

Generally, the rainfall CV in the Didessa River basin increases under all RCP scenarios compared to the 1984 –2014. Summer and autumn seasons were found to have greater rainfall variability than the annual and winter season. Breaking the total future time into shorter time intervals helps to identify the future time rainfall CV. Annual and seasonal rainfall showed greater variability at relatively low altitude sites than at high altitudes with few exceptions. Rainfall CV attains the highest value under the high emission scenario (RCP8.5) in the late 21st century. Rainfall in Ethiopia is affected by the intensity, position, and direction of Subtropical Jet, Inter-tropical Convergence Zone, Red Sea Convergence Zone and Tropical Easterly Jet multi-weather systems that lead to its variability in amount and distribution (NMSA, 1996).

Precipitation Concentration Index

Precipitation Concentration Index (PCI) helps to indicate the monthly distribution of a time series rainfall. This section of the article compares the monthly distribution of historical rainfall and future rainfall under the RCP scenario in the three future time intervals at six meteorological stations in the Didessa River basin.

Historical rainfall (1984 to 2014) monthly rainfall distribution at Arjo, Bedele, Nekemte, and Sire stations was found to be moderately concentrated while that of Dembi and Gimbi was in the category with a very high concentration. Monthly rainfall distribution under RCP2.6 at Dembi, Gimbi and Sire stations indicates strong irregularity except in the time intervals 2018 to 2043 and 2070 to 2095 at Dembi and Gimbi, respectively. Under this concentration pathway, the monthly rainfall distribution at Arjo and Nekemte is in the category with very high concentration in all three future time intervals while that of Bedele is in the category of moderate distribution. Under RCP4.5, the monthly rainfall distribution at Dembi, Gimbi and Nekemte is in the category with a very high concentration in all future time intervals. Very high monthly rainfall concentration is also found at Arjo, Bedele and Sire in the time intervals 2018 to 2043 and 2070 to 2095, respectively. Monthly rainfall distribution at Arjo, Bedele and Sire is under the category of moderate concentration in the time interval 2044 to 2069.

Under the higher scenario (RCP8.5), the monthly distribution of rainfall is in the category of very high concentration except at Arjo, Bedele and Sire in the time intervals 2070 to 2095 and 2018 to 2043, respectively, at all stations. Monthly rainfall distribution is more concentrated under RCP scenarios than under historical rainfall. In summary, the moderate monthly rainfall distribution at high altitudes shifted to the category very high concentration and very high concentration in monthly rainfall distribution at relatively low altitudes (Dembi & Gimbi) changed to a strong irregularity under RCP2.6 scenario. On average, rainfall distribution was found to be more concentrated at low altitudes than at high altitudes and under RCP2.6 than under RCP4.5 and RCP8.5 (Figure 6).

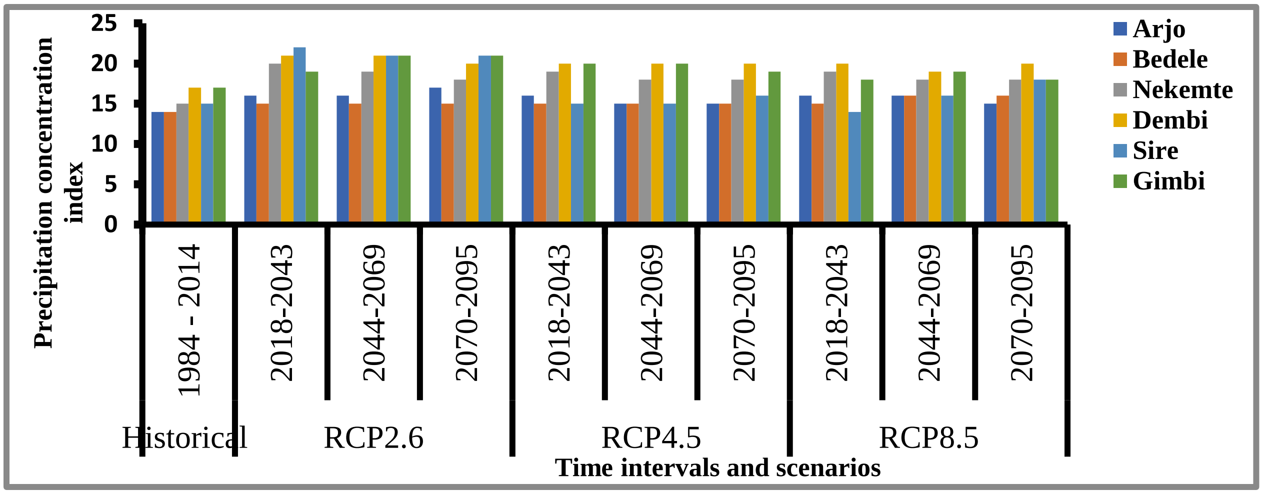

Figure 6: Computed summary of monthly historical and future PCI of the six meteorological stations under RCP2.6, RCP4.5 and RCP8.5

Standardized Rainfall Anomaly

Standardized Rainfall Anomaly (SRA) indicates a year or season with either lower or higher rainfall amount at a station compared to its long-period mean average rainfall amount. Changes in the percentage proportion of positive rainfall anomalies in the annual and seasonal time scales under the three RCP scenarios in the three future time intervals at 6 meteorological sites are discussed in this section. Changes in percentage proportions of negative rainfall anomaly were not presented as it can be estimated from the positive rainfall anomaly.

Numbers associated with negative signs (Table 1) indicate a decrease in the percentage proportion of positive rainfall anomalies while those without negative signs show an increase in that value in the respective stations, time intervals, RCP scenarios and time scales.

Table 1: Changes in percentage proportions of the number of years with positive SRA under RCP scenarios as compared with the respective historical SRA at six stations in the Didessa river basin in annual and seasonal time scales

		Annual			Summer			Autumn			Winter		
Stations	Time intervals	RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5
	2018-2043	17	-4	6	-14	21	-10	10	13	10	-1	10	-17
	2044-2069	21	2	-6	-2	2	-2	-2	44	13	14	-16	-13
Arjo	2070-2095	6	-21	-21	25	25	17	37	-21	13	10	3	3
	2018-2043	6	6	-6	6	2	-2	2	-2	-6	21	10	-2
	2044-2069	-2	6	-6	2	2	-6	-6	-14	-14	6	-2	-10
Bedele	2070-2095	-17	-14	-6	-17	9	-6	-14	-10	-6	-3	-13	-2
	2018-2043	0	-23	-16	19	15	11	13	6	-2	7	0	-16
	2044-2069	-8	15	-12	23	19	11	-2	-6	-17	-12	-8	-20
Nekemte	2070-2095	-23	-20	-8	-5	23	26	-13	-6	8	-20	-20	3
	2018-2043	35	12	-4	2	-2	-6	50	12	4	17	10	-2
	2044-2069	8	8	4	6	2	-6	4	4	-4	-6	2	-10
Dembi	2070-2095	-7	-7	8	-17	-10	-2	-7	-4	8	-10	0	2
	2018-2043	9	2	-6	12	8	8	19	12	12	13	10	-10
	2044-2069	-2	6	-2	19	12	8	16	4	12	2	6	2
Sire	2070-2095	-17	-17	-6	-7	23	8	-4	0	0	-10	-10	2
	2018-2043	-9	6	3	42	-1	11	-2	25	17	32	0	9
	2044-2069	-28	-20	3	7	9	15	-25	6	17	-14	9	-3
Gimbi	2070-2095	-5	-5	-24	34	7	-8	-2	6	-21	-7	-7	-14

The highest annual increase in the percentage proportion of positive rainfall anomalies was seen at Dembi in the early 21st century under RCP2.6, followed by Arjo in the mid 21st century under RCP2.6. In this time scale, the highest decrease in the percentage proportion of positive rainfall anomalies was found at Gimbi in the mid-21st century under RCP2.6.

In summer, the highest increase in the percentage proportion of positive rainfall anomalies was seen at Gimbi under RCP2.6 in the early 21st century, followed by the second highest value at the same station and scenario in the late 21st century. In this season, the highest decrease in the percentage proportion of positive rainfall anomalies corresponds to Bedele and Dembi both in the late 21st century under RCP2.6 (Table 1).

Considering the autumn season, the highest increase in the proportion of positive rainfall anomalies was found at Dembi in the early 21st century under RCP2.6, followed by that of Arjo in the mid 21st century under RCP4.5.The highest decrease in the percentage proportion of positive rainfall anomalies was found at Gimbi in the mid-21st century under RCP2.6 followed by that of Arjo and Gimbi in the late 21st century under RCP4.5 and RCP8.5, respectively, (Table 1).

In the winter (main rain season) that extends from June to September, the highest increase in the proportion of positive rainfall anomalies was found at Gimbi, followed by that of Bedele in the early 21st century under RCP2.6. In this season, Nekemte station was found to have the highest decrease in the percentage proportion of positive rainfall anomalies in the mid 21st century under RCP8.5 and in the late 21st century under RCP2.6 and RCP4.5 (Table 1).

Changes in rain season onset, cessation, and length under future periods

Onset and cessation in days of the year (DOY), which were the bases for the computed changes and length of rain season were described in Table 2. Rain season onset delay in all future time intervals under all RCP scenarios at all stations considered in the river basin. It was observed that the delay in rain season onset may vary in the length of days among the time intervals, the scenarios considered, and the stations. Arjo and Bedele stations may experience longer delay in rain season onset. However, these two stations receive higher mean average annual rainfall than Dembi and Sire stations with relatively early rain season onset (Figure 7).

Table 2: Mean historical and future rain season onset, cessation and length at six meteorological stations in the Didessa river basin

Time interval	Station	Rain season onset (DOY) His	RCP 2.6	RCP 4.5	RCP 8.5	Rain season cessation (DOY) His	RCP 2.6	RCP 4.5	RCP 8.5	Rain season length (days) His	RCP 2.6	RCP 4.5	RCP 8.5
2018-2043	Arjo	103	126	130	127	311	318	320	285	208	191	190	158
	Bedele	108	140	145	139	315	306	307	305	207	166	161	167
	Nekemt	114	128	125	125	312	263	283	274	198	134	157	149
	Dembi	121	127	128	127	306	268	268	268	185	141	140	141
	Sire	113	123	116	116	299	268	285	291	186	145	169	175
	Gimbi	114	131	141	134	311	307	276	315	196	176	134	181
2044-2069	Arjo	103	127	136	127	311	300	325	280	208	173	188	152
	Bedele	108	145	138	146	315	305	306	312	207	160	168	166
	Nekemt	114	125	124	129	312	267	314	320	198	142	189	190
	Dembi	121	125	123	129	306	267	269	270	185	142	146	141
	Sire	113	116	118	128	299	270	307	276	186	154	189	147
	Gimbi	114	138	150	133	311	276	266	269	196	138	116	136
2070-2095	Arjo	103	127	140	130	311	269	324	320	208	141	185	190
	Bedele	108	144	143	131	315	304	289	284	207	160	146	153
	Nekemt	114	126	126	134	312	275	314	305	198	148	188	170
	Dembi	121	124	127	143	306	267	268	270	185	144	141	127
	Sire	113	123	135	130	299	270	276	269	186	147	141	140
	Gimbi	114	138	149	129	311	275	265	290	196	137	116	161

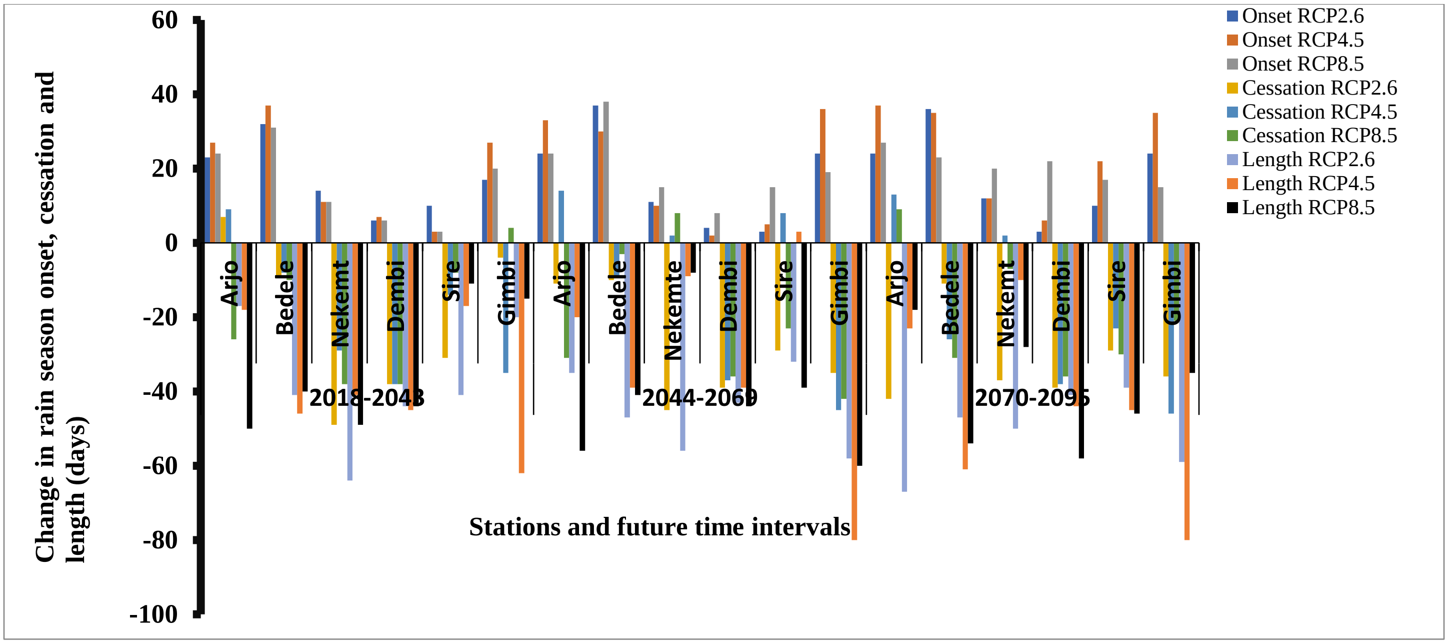

Figure 7: Changes in rain season onset, cessation, and length under RCP scenarios in three future periods at six stations in the Didessa River basin with reference to 1984-2014

There is an early rain season cessation in the early, mid, and late 21st century, under all RCP scenarios at all stations considered except at Arjo, Nekemte, and Sire where a few positive values were observed (Figure 7). The study report indicates that anomalous mid-troposphere moisture divergence and northward shift of Sahel rainfall severely curtail the long rains in East Africa (Cook and Vizy, 2012).

Length of rain season decreases in the early, mid, and late 21st century under all RCP scenarios at all stations considered except at Sire under RCP4.5 in the time mid 21st century. Here it was observed that the length of days by which rain season length decreases varies among the time intervals, the scenarios considered, and the stations (Figure 7). A simulation study using Csiro-mk3-6-0, HadGEM2-ES, and MIROC-ESM-CHEM models indicated a shortening of autumn and winter rainy season length in the time interval 2021 to 2040 under RCP4.5 compared with the historical rain season length in the period 1992 to 2012 at all stations considered in North Eastern Amhara Region of Ethiopia (Ampaire *et al*., 2015).

Future changes in maximum and minimum temperature

Observed historical and simulated future temperatures were compared in the moist humid Didessa River basin and the changes were presented in Figures 8 and 9. Further details were also indicated in Appendix Tables 4 & 5. In the early 21st century, the average maximum temperature rose by 0.95 ºC, 0.88ºC, and 1.01 ºC under RCP2.6, 4.5, and 8.5, respectively, from the historical mean average over 1984 to 2014. The mean average minimum temperature decreased by 2.2 ºC, 1.3 ºC, and 0.27 ºC under RCP2.6, RCP4.5, and RCP8.5, respectively in the river-basin (Figure 8 & 9).

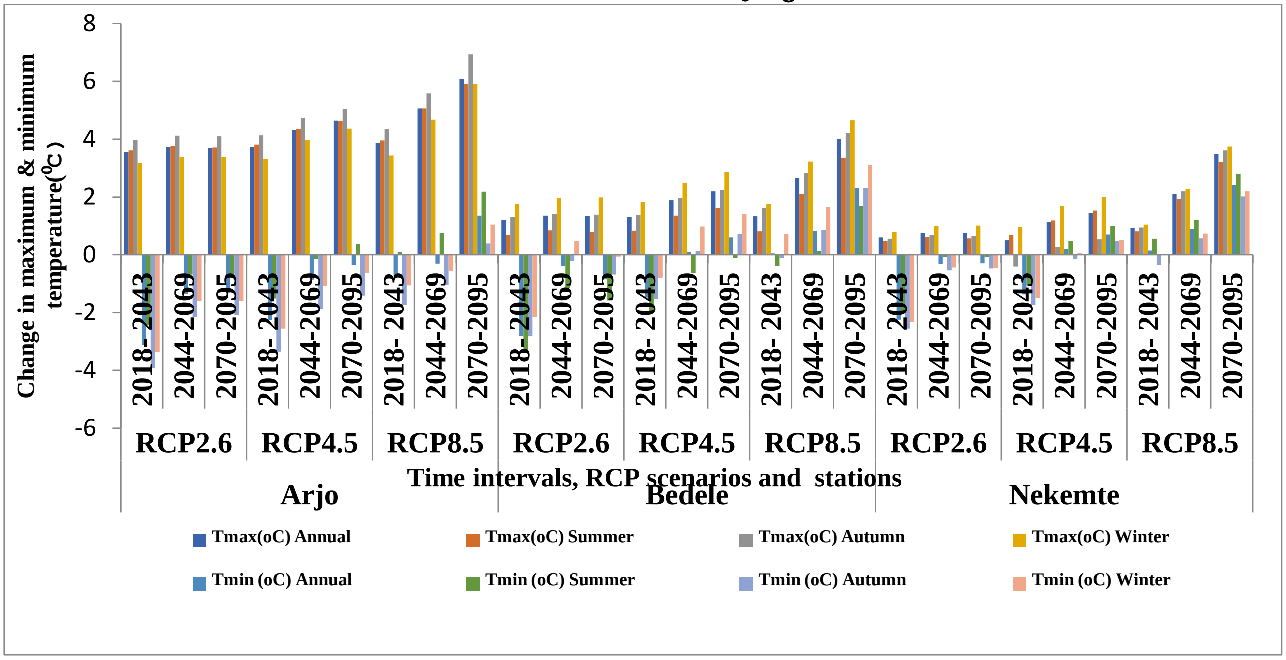

Figure 8: Future seasonal and annual changes of average maximum, and minimum temperature under RCP scenarios in near, mid, and long-term periods in the 21st century

In the mid-21st century, the mean average maximum temperature rose by 1.1 ºC and the mean average minimum temperature decreased by 0.52 ºC under RCP2.6. Mean average maximum and minimum temperature rise by 1.5 ºC and 0.58 ºC, respectively, under RCP4.5 in this time interval. Mean average maximum and minimum temperature rise by 2.2 ºC and 1.1 ºC, respectively, under RCP8.5 (Figure 8 & 9).

In the late 21st century, the mean maximum temperature rose by 1.35 ºC and 1.81 ºC, respectively, under RCP2.6 and RCP4.5 concentration pathways. On the other hand, the mean minimum temperature decreases by 0.87 ºC, and increases by 0.92 ºC under RCP2.6 and RCP4.5 scenarios, respectively. Under the higher concentration pathway (RCP8.5), the mean maximum and minimum temperature increased by 3.58ºC and 2.7 ºC in the late 21st century compared with the historical mean temperature (Figure 8 & 9). The finding is consistent with reports of Geleta, et al. (2022) who also found incremental changes both in maximum and minimum temperature near the current study area employing CORDEX Africa multi-model ensemble.

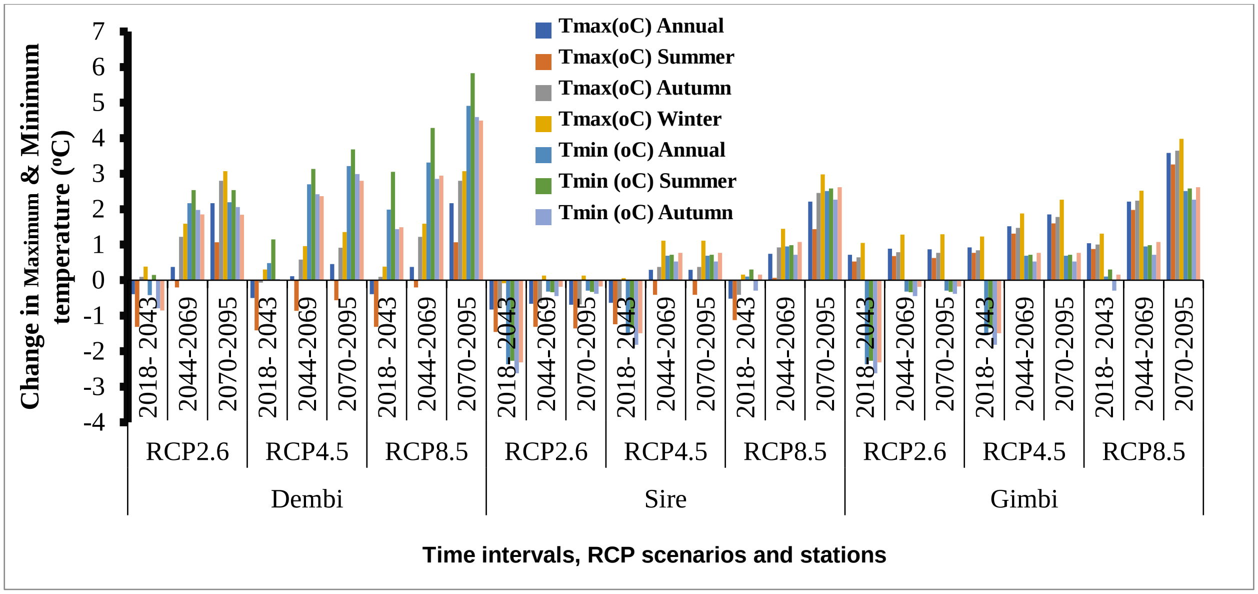

Figure 9: Future mean maximum and minimum temperature changes at Dembi, Sire and Gimbi stations

An increase in temperature in the early, mid, and late 21st century compared to historical (1986 to 2005) temperatures using CORDEX Africa climate model ensemble mean indicated the highest rise under RCP8.5 (Legesse, 2017). Climate models such as Gfd1, HadGEM2-ES, MIROC5, and NORESM1-M in CORDEX Africa are included in this study. Similar studies in Northwestern Ethiopia also reported increases in maximum and minimum temperature from 1.55˚C to 6.07˚C and from 0.11°C - 2.81°C, respectively, in the 2080s using CMIP3 SRES scenarios by (Ayalew *et al*., 2012).

Conclusion

Annual rainfall at higher altitude stations increases under all RCP scenarios while it decreases at lower altitude stations in the 2030, 2050 and 2080's under all RCP scenarios of the 21st century. Winter (June to September) rainfall also increases at higher altitude sites except at Nekemte throughout the 21st century. The season rainfall decreases at lower altitude stations in all three time periods of the 21st century under all RCP scenarios. In Autumn (February to May), the rainfall amount increases at relatively higher altitudes while it decreases at lower altitudes in all future time intervals of the 21st century under all RCP scenarios, while it decreases at lower altitudes in all future time intervals under all RCP scenarios. The seasonal rainfall decreases at Bedele under RCP4.5 and RCP8.5. Autumn seasonal rainfall CV decreases at higher altitude stations in 2030 and 2050 under all RCP scenarios. On the other hand, the seasonal rainfall CV increases at lower altitude stations in the 2080's. Late-onset and early cessation of the rainy season are expected under all RCP scenarios in all future time intervals in the majority of stations. The length of the rainy season decreases under all scenarios in all future time intervals at all stations. Future maximum temperature rise by 2.2 ºC in the early and mid 21st century and by 3.58 ºC in the late 21st century under RCP8.5. Generally, future rainfall under RCP scenarios in the Didessa River basin will experience temporally and spatially variable change while temperature increases. The output of this research finding will complement the sustainable development of the Didessa river basin in devising the planning of adaptation and mitigation climate action.

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Conflict of interest

There is no any conflict of interest among the authors.

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