Assessment of the Potential Impacts of Climate Change in Agricultural Catchment: The Case of Fincha, North western Ethiopia

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Abstract

The relevance of agriculture to the promotion of sustainable development largely depends on the availability of water resources. Climate change affects water resource by altering the magnitude and patterns of hydrological process. This study was aimed at evaluating the potential impacts of climate change on hydrological process of Fincha catchment, upper Blue Nile basin. The ensemble mean of regional climate models (RCMs) in coordinated regional climate downscaling experiment (CORDEX)-Africa was used based on high emission scenario (RCP8.5) and medium emission scenario (RCP4.5). Soil and Water Assessment tool (SWAT) hydrological modeling was used to evaluate the impacts of climate change. The result shows a decreasing precipitation by -8.24% to -11.32% under RCP4.5 and -7.87% to -9.67% under RCP8.5 in 2021-2050 and 2051-2080, respectively. The temperature will increase under both RCPs. The decline of precipitation and increase of temperature reduces surface flow, groundwater and water yield. The increase in Evapotranspiration due to increased temperature and higher evaporation demands coupled with a decreasing precipitation leads to a reduced soil moisture. This could reduce the availability of water for crop production, which will be a chronic issue to the subsistence agriculture. The increase in seasonal and annual variation of precipitation and temperature increased the frequency of hot and dry years that will lead to serious water scarcity that aggravate water stress in the catchment and further downstream. Consequently, strong mitigation and adaptation through land and water management by coping with water scarcity in agriculture and water productivity is indispensable to manage the risks.

Keywords: Ensemble, Fincha, Rainfall, RCMs, water resources

Introduction

Land and water resources are fundamentally linked to the global and regional challenges of food security, degradation and depletion of natural resources (FAO, 2011) owning to their pivotal role for agriculture production, urban and rural developments. However, the global and regional climate changes have become the major threats of the resources. This change is expected to produce detrimental environmental effects such as lowering potential productivity, which is essential for productive and resilient agricultural systems and declines the products and services of the livelihood.

Climate change hampers agricultural yields through disturbing the agro-ecological environment (Chhogyel & Kumar, 2018; Raza *et al.*, 2019) and exacerbates the current stress of water resources availability (Bates et al., 2008). This spurred an interest into the effects on water resources on which many nations like Ethiopia are preferring their development activities.

Regardless of the changes in climate and its impacts, different studies projected climate changes with different degrees of change. Dile *et al*. (2013) in Gilgel Abay projected a decreasing precipitation during 2010-2040 but increases in 2070-2100 while Shiferaw *et al.* (2018) on Ilala watershed reported an increasing temperature, however rainfall does not show significant change. Recent study in Rift valley revealed a decreasing precipitation and increasing temperature (Gadissa et al.,2018). It can be seen, temperature is increasing however there is no consensus among studies on the direction of the projected precipitation. Overall, the studies revealed the climate change impacts on future seasonal and annual hydrological variables is increasing stresses of water resources availability. However, how climate change continues to interact and disturb the land and water resources varies from global to region and region to local scales. Hence, research that could improve our understanding of the extent to which climate change affects the regional water resources, agriculture and environment is vital.

In recent past, rapid population growth with the expansion of commercial farm, deforestation and cultivation lands coupled with rapid urban expansion in Finchaa catchment have brought severe land and water resources degradation (Dibaba et al., 2020a). Furtherrmore, the highly rising demands of water in Finchaa catchment owning to the socio-economic progresses and high demand of irrigation water for sugarcane cultivation are increasing pressure on water resources of the catchment.

The regional to local information on climate change helps to define susceptibility of the land and water resources and reveals the process and mechanisms of regional changes that could help to plan appropriate management system (Shawul *et al.*,2019). In this study, an integrated approach of climate change modeling and hydrological modeling was used to assess the climate change at catchment level and explore the potential impacts of the changes in Finchaa agricultural dominated catchment.

Materials and Methods

Study area

The study area, Finchaa is an agricultural catchment in North western part, Oromia Regional State, Ethiopia. The catchment is mainly characterized by agricultural land with some range lands around the downstream of the catchment and wetlands around the head of Abay Chomen reservoir, upstream of the catchment. Geographically the catchment is located in 9°10' to 10°00' North latitude and 37°00' to 37°40' East longitude with a total area of 3781km2. The description of the study area is shown by Figure 1.

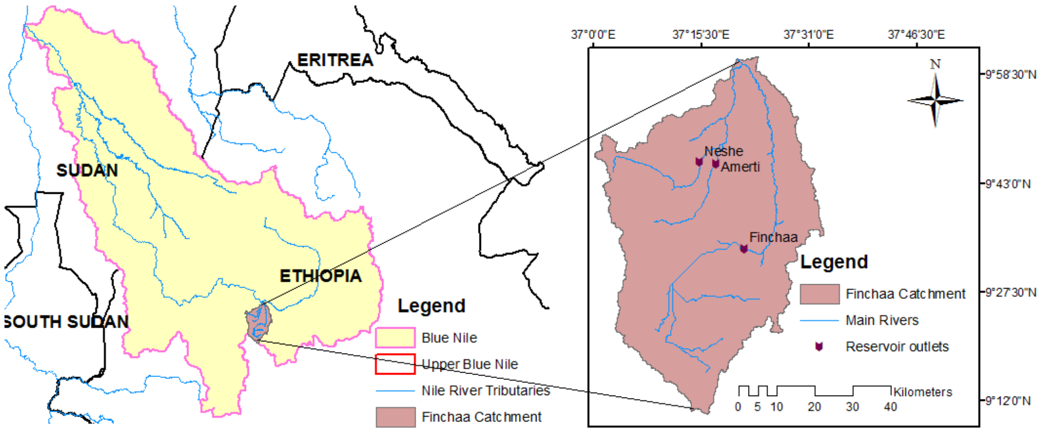

Figure 1. Map of the study Area

Agriculture is the major activity and occupation of the community in Finchaa catchment. Although most of the community in Finchaa catchment is depending on agriculture, farming system in the catchment is constrained by the complex topography, soil and land degradation and variability environmental changes (Dibaba *et al.*, 2020a; Tefera & Sterk, 2010)

Data collected

The study used spatial (DEM, soil and land use/land cover), temporal (meteorological and hydrological) and Regional Climate Models data. Digital Elevation Model (DEM) of 30m x 30m downloaded from the United States Geological Survey (USGS) at https://earthexplorer.usgs.gov/ was used for watershed delineation, slope and physical catchment characteristics generation. The soil data required for the study was collected from the Ministry of Water, Irrigation and Electricity, and classified according to the FAO classification system. The land use/land cover data of 2017 derived from Landsat 8 operational land imager (OLI) used in this study was developed by Dibaba et al. (2020a).

The observed meteorological data from five weather stations inside the catchment was collected from the National Meteorological Service Agency (NMSA) of Ethiopia. These stations were selected based on their record length and percentage of missed data. Inverse Distance Weighting (IDW) was used to the missing data values of the stations. A stream flow data was collected from the Ministry of Water, Irrigation and Electricity hydrology department for the years 1987-2007.

Methodology

Climate change scenarios and their impact assessment

Four Regional climate models (CCLM4-8, HIRHAM5, RACMO22T and RCA4) showing better performance were selected after evaluating the performance of six Regional Climate Models used in Coordinated Regional Climate Downscaling Experiment (CORDEX) Africa. The detail evaluation of the CORDEX-RCMs in Finchaa catchment presented by Dibaba et al. (2019) indicated, the ensemble mean outperforms the individual RCMs.

The evaluation of the climate change was based on two future periods denoted by near future (2021-2050) and mid-future (2051-2080) with a baseline/historical period of 1986-2015 under mid-range mitigation emission scenario (RCP4.5) and high emission scenario (RCP8.5). The RCMs output from CORDEX-RCMs were bias corrected against the observed precipitation and temperature using the distributed mapping technique in climate model data for hydrological modeling (CMhyd). Then, the potential impacts of the climate change under the historical and future scenario was assessed using Soil and Water assessment tool (SWAT) model.

Soil and Water Assessment Tool

The SWAT is a physically based semi-distributed model that drives on a continues time scale at catchment scale (Arnold *et al.*, 1998). SWAT Model was developed to simulate the impact of land management and climate change on hydrology, sediment, water quality and nutrients over long periods in agricultural watersheds on daily, monthly and yearly bases. The SWAT predicts the hydrological process at each hydrological response unit (HRUs) based on the water balance equation (Neitsch et al., 2011) given in equation 1. The catchment is divided into sub-basins that contain one or more HRUs. The HRU is the smallest unit for the catchment physical process discretized based on the homogeneity of the land use, soil type and slope classes.

$$SWt = SWo + \sum_{i=1}^{t}(Rday - Qsurf - Ea - Wseep - Qgw) \quad (1)$$

Where, SW*t* is the final soil water content(mm), SW*o* is the initial water content(mm), t is the time(days), R*day* is the amount of precipitation on day I(mm),Q*surf* is the amount of surface runoff on day I (mm), E*a* is the amount of evapotranspiration on day I(mm), W*seep* is the amount of water entering the vadose zone from the soil profile on day I(mm) and Q*gw* is the amount of return flow on day I (mm).

The model allows the simulation of different hydrological and physical process occurring in the watershed (Neitsch et al., 2011). The major model outputs are primarily discharge of the major and tributary streams with water balance components of the watershed.

SWAT Performance Evaluation

Sensitivity Analysis, Calibration and validation

Sensitivity analysis is done with the aim of identifying the most influencing parameters on the model output. The Calibration and Uncertainty Program (SWAT-CUP) used the Sequential Uncertainty Fitting (SUFI-2) program for sensitivity analysis, calibration and validation (Abbaspour, 2015). Calibration process involves the estimation of model parameters by comparing the model prediction with the observed data under the same condition (Moriasi *et al.*, 2007, Abbaspour, 2015). Validation is testing the calibrated model without further parameter adjustments in an independent dataset. The observed stream flow data of 1987-2007 was split into a warm-up (1987-1989), calibration (1990-2000) and validation (2001-2006) period.

The evaluation of the predictive capability of the SWAT simulation with respect to the observed stream flow was expressed by coefficients of determination (R^2) and Nash-Sutcliffe efficiency (NSE). The higher R^2 value indicates less error. NSE ranges from negative infinity to 1(best). These statistics are calculated using equations 2 to 3.

$$R^2 = \frac{\sum_{i=1}^{n}[(Qmi-\bar{Q}m)(Qsi-\bar{Q}s)]^2}{\sqrt{\sum_{i=1}^{n}(Qmi-\bar{Q}m)^2\sum_{i=1}^{n}(Qsi-\bar{Q}s)^2}}; 0 \le R^2 \le 1 \qquad (2)$$

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}(Qmi-Qsi)^2}{\sum_{i=1}^{n}(Qmi-\bar{Q}m)^2}; -\infty \le \text{NSE} \le 1 \qquad (3)$$

Where Qm is the measured discharge, Qs is the simulated discharge and $\bar{Q}m$ is the average measured discharge and $\bar{Q}s$ is the average simulated discharge.

Result and Discussion

Sensitivity analysis, calibration and validation of the SWAT model

The most sensitive parameters of flow prediction was SCS runoff curve number-CN2, (runoff process), followed by soil available water capacity-SOL_AWC (soil parameter) and deep aquifer percolation fraction-RCHRG_DP (groundwater parameter (Table 1). The most sensitive parameters, curve number and soil available water capacity in the catchment are directly related to the land use/land cover and soil characteristics.

Table 1. Sensitivity analysis and calibrated parameters

		Sensitivity				Calibration	
Par	Parameter Name	File type	t-Stat	P-Value	Sensitivity Rank	Parameter value range	Fitted Value
1	r__CN2	.mgt	-18.58	0.00	1	±25%	-1.548%
12	r__SOL_AWC	.sol	-4.79	0.00	2	±25%	4.62%
2	a__RCHRG_DP	.gw	-3.40	0.00	3	0-1	0.008
9	v__CH_K2	.rte	-2.22	0.03	4	5-130	107.71
4	a__GW_DELAY	.gw	-1.79	0.07	5	±10	-4.342
3	v__ALPHA_BF	.gw	1.47	0.14	6	0-1	0.449
15	v__SLSUBBSN	.hru	-0.83	0.41	7	10-150	71.909
6	a__GW_REVAP	.gw	-0.58	0.56	8	±0.036	0.0004

Key: r-denotes multiplying initial parameter value by its percent, v-replacement of the initial value of the parameter, a-adding value to initial parameter value

The SWAT calibration revealed that the model was able to capture the observed stream flow with R^2 and NSE of 0.71 and 0.71 respectively. The validation of the model also shows a good agreement with R^2 and NSE of 0.81 and 0.76 respectively. In general, the calibration and validation results showed fairly good agreement between the simulated and observed flow (Figure 2). Hence, SWAT model is good enough to be used in planning watershed modeling of Finchaa catchment as the model simulation captured the observed flow of the catchment.

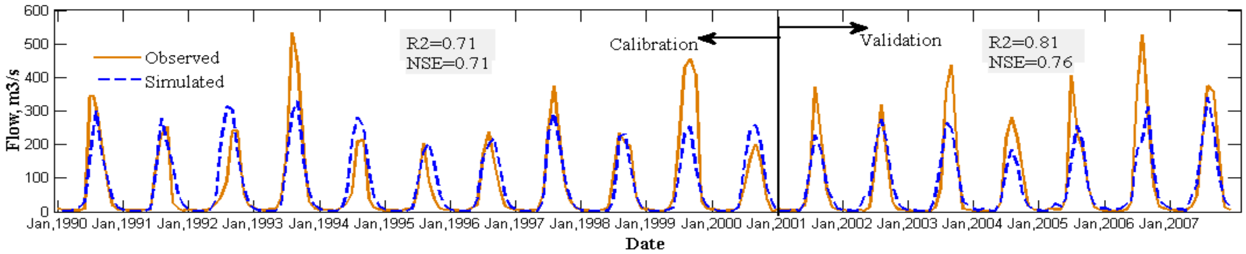

Figure 2. Calibration and validation of average monthly stream flow

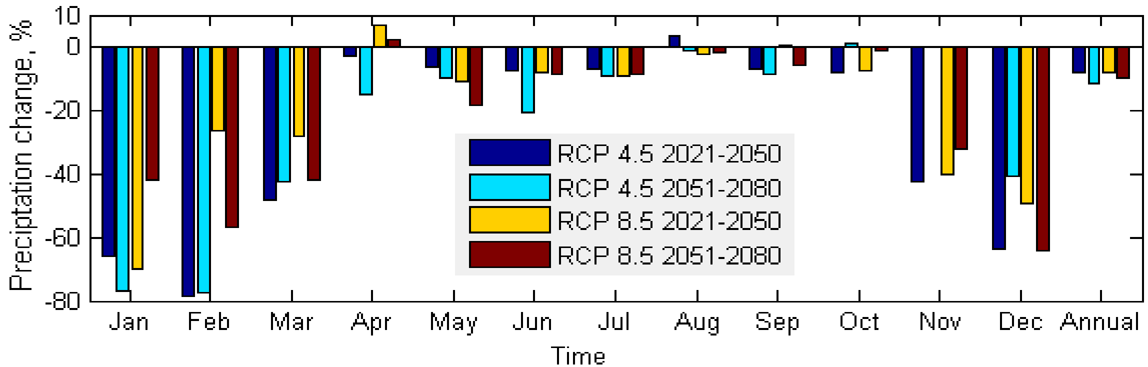

Figure 3. Seasonal changes of precipitation change in Finchaa catchment (Dibaba et al., 2020b).

Climate change projections of Ensemble RCMs

Climate change was evaluated in terms of the annual and seasonal changes of precipitation, maximum and minimum temperature. Accordingly, the change in precipitation varies from -8.24% under RCP4.5 to -7.87% under RCP8.5 in near future and varies from -11.32% under RCP4.5 to -9.67% under RCP8.5 in the mid future. Overall, the ensemble mean of the RCMs projection shows, precipitation declines under all scenarios.

The seasonal precipitation decline is higher in the dry season than wet season. The seasons that experience the highest precipitation in the catchment (JJAS) experiences lower decline of precipitation. The dry seasons will experience a higher decreasing precipitation under all scenarios (Figure 3).

A study by Seleshi & Camberlin (2006) also reported a decreasing trend of precipitation intensity using data from 1965 to 2002 in eastern, southwestern and southern regions of Ethiopia. The results of decreasing precipitation projections are consistent with the results presented by climate change studies (Dile et al., 2013, Gadissa et al., 2018). However, there are also studies that projected a decreasing precipitation over Upper Blue Nile River basin. Using statistical downscaling techniques, Mekonnen & Disse (2018) projected increasing trends of precipitation by 1 to 14.4%. Similarly, Gebre & Ludwig (2015) reported an increase of future precipitation over Tana basin. Although there are studies that projected an increase in precipitation, the observed precipitation of the last century showed a decrease of precipitation over Africa (IPCC, 2013). From 17 climate models, most of them (10) reported reduction than increases (7) (Elshamy, Seierstad, & Sorteberg, 2009). The differences among the climate change studies could be due to the techniques of downscaling, types and resolution of GCM-RCMs combinations and their associated boundary conditions.

The projection of maximum and minimum temperature shows, both temperature will increase under all scenarios. Accordingly, the change in maximum temperature varies from 1.34^{o}C under RCP4.5 to 1.49^{o}C under RCP8.5 in near future and from 2.15^{o}C under RCP4.5 to 3.21^{o}C under RCP8.5 in mid future. Similarly, the change in minimum temperature varies from 1.57^{o}C under RCP4.5 to 1.92^{o}C under RCP8.5 in near future and from 2.67^{o}C under RCP4.5 to 4.23^{o}C under RCP8.5 in mid future.

Although the change in projection of both maximum and minimum temperature shows increasing trend, the changes vary with the emission scenario and the future periods. The temperature change is higher for higher emission scenarios (RCP8.5) than medium emission scenarios (RCP4.5) and higher in the mid future (2051-2080) than the near future

(2021-2050). This confirms RCP8.5 is warmer than RCP4.5. Further, the analysis of the temperature change reveals, the increase of the daily minimum temperature is higher and more rapidly than daily maximum temperature leading to the increase of the daily mean temperature.

The variation in changes of temperature is not only limited to annual, rather temperature change also varies seasonally. Like the magnitude of the changes, the seasonal variations are higher for minimum temperature than maximum temperature. Wet seasons are expected to have higher minimum temperature change than the dry seasons as shown by Figure 4.

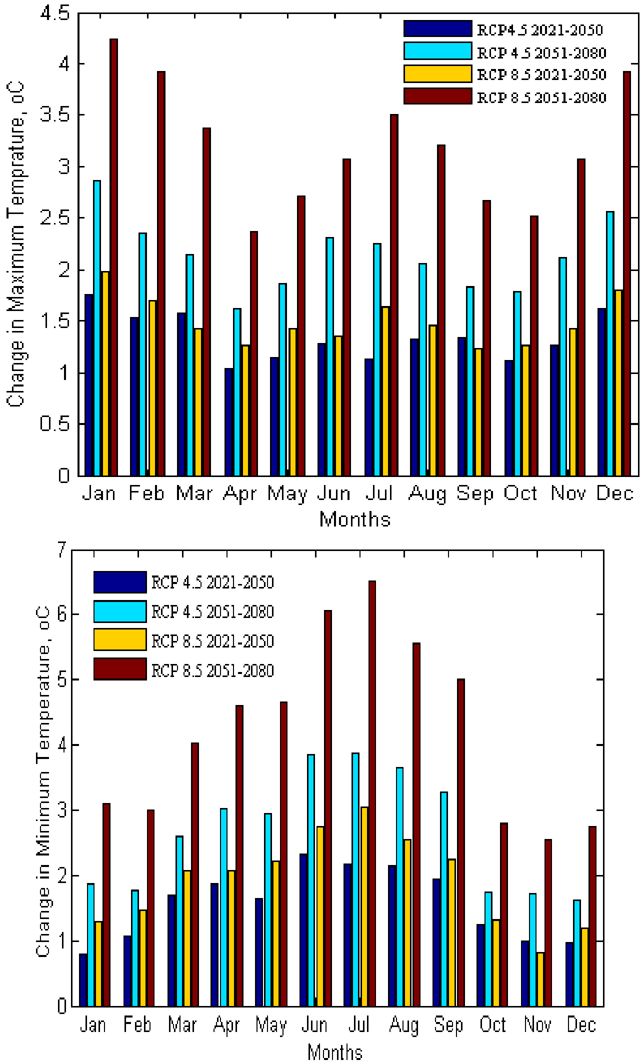

Figure 4. Seasonal changes of maximum temperature and minimum temperature.

Climate change studies in Ethiopia reported similar trends of temperature change but with varying degrees based on the downscaling techniques and types of climate model. GFDRR (2011) reported mean annual temperature is projected to increase by 1.1 °C to 3.1 °C by the 2060 and 1.5 °C to 5.1 °C by 2090s. Likewise, Beyene etal, (2010) reported increasing annual temperature from 0.91 °C to 1.9 °C during 2010-2039 using the ensemble of 11 GCMs over upper Blue Nile basin.

Overall, it can be seen temperature is increasing however there is no harmony among studies on the direction of the projected precipitation. The complexity in nature of precipitation and its dependency on topographic and physical factors coupled with high inter-annual and inter-decadal variability of rainfall in Ethiopia could contribute to this. Hence, the use of multiple GCM-RCMs could help in improving the uncertainties of climate models associated with individual RCMs.

The potential impacts of climate change

The decline of precipitation and increase of temperature lead to a reduced surface runoff (SQ), groundwater (GW) and overall water yield (WY) while potential evapotranspiration (PET) gets increased under both scenarios (Figure 5). The decline of SQ ranges from -7.33% under RCP4.5 in near future to -14.48% under RCP4.5 in mid future. Whereas, the decline of GW varies from -9.21% under RCP4.5 in near future to -15.86% under RCP8.5 in mid future. The decline of WY yield varies from 8.49% under RCP4.5 in near future to -13.77% under RCP4.5 in mid future. Whereas, the increase in PET varies from 16.31% under RCP4.5 in near future to 22.89% under RCP8.5 in mid future. The increase in evapotranspiration is attributed by the increase in vapor pressure deficit owing to the higher temperature and the increase of PET could be the factor for the decline of WY.

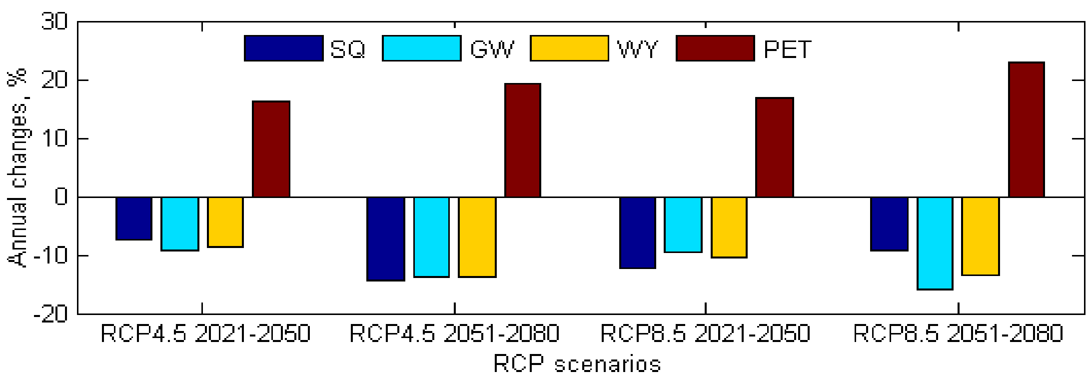

Figure 5. Changes of water balance components under a climate change

Although climate change affects both surface water and groundwater, assessment of climate change impacts on GW is difficult as it requires further subsurface investigation. However, it can be noticed that any variation of the precipitation with changes in vegetation, temperature and evapotranspiration affects GW recharge. However, the rates of changes in GW due to climate change are more likely slow than changes in surface water.

Generally, the potential impacts of climate change are changes in stream flow and runoff characteristics, altered frequency and distribution of precipitation patterns, altered GW recharge and discharge rates and increased atmospheric evaporative demand-changes in evapotranspiration process. This alters flow regime and change nutrient and sediment budgets of watersheds and decreases water availability affecting vegetation survival and growth. The overall decline of annual flow is mainly due to the decline of the seasonal flows as stream flow is mainly controlled by seasonal patterns of precipitation and temperature. The warmer and drier seasons projected under both scenarios could increase the amount and magnitude of low flow days that further aggravate water stress in the catchment and downstream. Similar study in Blue Nile basin also revealed, the seasonal and annual variation of the future temperature shows the increased hot and dry years that will lead to serious water scarcity (Coffel et al., 2019).

Climate change studies on sub-Sahara also confirmed similar findings of warming trends of climate projections in inland subtropics, increasing aridity and changes in rainfall (Serdeczny et al., 2016). Beyene et al. (2010) on Nile River reported a decline of flow during the mid-2040-2069 due precipitation decline and increased evaporation demand. Using ensemble of five GCMs, Shiferaw et al., (2018) also confirmed the decline of the projected surface runoff under both RCPs due to the climate change. The extreme temperature which is either above or below the thresholds at critical times during the development also affects plant growth, plant reproductive process and pollination stage of fruit set (Hatfield & Prueger, 2015). In general, the effects of temperature change through increased water deficits highly affects the availability of water for crop production, which is chronic to the farmers in the catchment whose livelihood is based on agriculture.

In the study area, we have compared the combined effects of land use/land cover and climate change, and found that the impacts of climate change is more decisive than the impacts of land use/land cover (Dibaba et al., 2020b). However, uncertainties are pertinent to models. In this regard, this study should not be used as the actual result but as the indicators of future climate changes and water balance components with invaluable insights on the risk assessment of climate change on Finchaa catchment.

Conclusion

The ensemble mean of the RCMs projection shows, annual precipitation declines under all scenarios. The seasonal changes of precipitation shows, seasons that experience the highest precipitation is expected to have lower decline of precipitation than the dry seasons. The projections of the temperature change show the increase of the daily minimum temperature is higher and more rapidly than daily maximum temperature.

Changes in stream flow and runoff characteristics, altered frequency and distribution of precipitation patterns, altered groundwater recharge and increased atmospheric evaporative demand-changes in evapotranspiration process are the major potential impacts of climate change. The seasonal patterns of precipitation and temperature added with the catchment physical characteristics controls stream flow. The warm and dry seasons projected under both scenarios could increase the amount and magnitude of low flow days. Consequently, the catchment is highly exposed to the potential impacts of climate change that could range from warming to crop failures as a result of prolonged dry seasons.

The study provided important information on the relative influences potential climate change in agricultural catchment. This helps to plan the proper water resources management interventions. Especially if the degraded sloppy lands are rehabilitated, the ground recharge will increase and surface runoff which washes the top soil in to the lakes will get reduced. In general, the result highlights the need for regional developments and cooperation to urge for strong climate resilient management strategies for the rapid climate changes in the catchment.

Relatively, the regional projections of drought and soil moisture remain uncertain in comparison to the other components of hydrological process. Hence, assessing how climate change affects soil moisture and drought needs to be studied in the area.

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