International Journal of
Environmental Sciences & Natural Resources
ISSN: 2572-1119

Juniper Publishers
key to the Researchers

Review Article
Volume 23 Issue 4 - March 2020
DOI: 10.19080/IJESNR.2020.23.556119

Int J Environ Sci Nat Res

Precipitation and Temperature Projections for Medium-High Emission Scenario by General Circulation Models for Ethiopia

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Submission: January 21, 2020; **Published:** March 02, 2020

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Abstract

Climate predictions provide probabilities of long-term changes to the statistics of future climatic variables. Global circulation models are used to simulate local climate trends relative to global scale despite that they are challenged by natural variability; uncertainty arising from past, present and future forcing of the climate system by natural and anthropogenic forcing agents. The spatial resolutions of those models are counted in thousands of square kilometers and this might lead to lose the regional and local details of climate. The main objective of this meta-data analysis is to look into which model, among the total 16 considered in this case, best replicate the observed climate and simulate precipitation and temperature changes in Ethiopia. I have used historical and projected open data of precipitation and temperature from World Bank group for Ethiopia for the medium-high emission scenario. The base period for historical observation is 1986-2005 and the periods for future projection are 2020-2039, 2040-2059, 2060-2079 and 2080-2099 for the variables of interest mean monthly precipitation and temperature. The correlation coefficient has been used to indicate how capable each model is to replicate the mean monthly precipitation and temperature data for the period 1986-2005. The meta-data analysis indicated that the standard deviations for precipitation between the models for the periods 2020-2039, 2040-2059, 2060-2079 and 2080-2099 are 324.20, 320.38, 317.61 and 332.70, respectively. On the other hand, the standard deviations for the mean temperature for the consecutive periods are 0.85, 0.87, 0.90 and 0.92, respectively, showing less variation among the models' simulation. That means, for Ethiopia through the different periods, temperatures are better replicated by almost by all 16 global circulation models than precipitation.

Keywords: Ethiopia; GCM; Observed climate; Projection; Uncertainty

Introduction

Climate predictions provide probabilities of long-term changes to the statistics of future climatic variables (including average temperature and rainfall as well as their standard deviation). Climate projections by General Circulation Models (GCMs) are challenged by natural variability; uncertainty arising from past, present and future forcing of the climate system by natural and anthropogenic forcing agents such as greenhouse gases (GHGs),, aerosols, solar forcing and land use change; and the response of the climate system to the specified forcing agents. In addition, quantifying the uncertainty that arises from each of the three sources has added another important challenge [1]. Again, these have been supplemented by scenario and model uncertainty challenges.

There are opposing arguments about GCMs. For instance [2], climate change sceptics argue that "models are unreliable" while the climate change believers argue that "models successfully reproduce temperatures since 1900 globally, by land, in the air and the ocean." The doubt of the sceptics might arise due to parametric uncertainty (e.g. data quality on a certain variable) and structural uncertainty (e.g. poor understanding of the relationships between two or more variables) which also more or less argued by some of the believers of climate change. The latter suggested that the models help us improve our understanding and prediction in global processes; allow us to determine the distinct influence of different climate features, used for diagnosis and prognosis.

Regardless of the confidence given by IPCC to the (GCMs) to simulate future climate and attribute observed climate change to anthropogenic emissions of GHGs, utilized to advance our understanding of current and past climate, provide qualitative and quantitative information about potential future climate, they remain deficient in many aspects of their representation of the climate, which reduces their ability to provide reliable imitations of future climate [3-6]. The GCMs are built on the assumption that increased concentration of GHGs in the atmosphere will have a significant change in temperature and precipitation [4]. Although GCM simulation is a tool to simulate local climate trends relative to global scale, they do not completely characterize the small-scale features of a particular region [7,8].

Although there are some improvements in GCMs nowadays than previous [9,10], like the inclusion of aerosol indirect effects, and direct effects in the radiation code in CAM5; formulations of radiation, boundary layer, and aerosols; and inclusion of the effects of land use change, they are remained coarser resolution at regional and local scales. The spatial resolutions of GCMs are counted in thousands of square kilometres and this might lead to lose the regional and local details of climate, especially in a country like Ethiopia which has a heterogeneous spatial physiography. When a coarse spatial resolution of GCM, say 50 km by 50km that equals to 2500km^2, is divided by the total area and made standardized, it loses the level of confidence when applied to simulate local level precipitation and temperature changes (Figure 1). The response of the Earth system to changes in radiative forcing's and the ways in which humankind responds through changes in technology, economies, lifestyle and policy will determine the implications of climate change for the environment and society. These issues might not be assessed by the old scenarios and hence need to create new scenarios which will answer the most challenging and important questions about climate change confronting the global community [11-13]. Which GCM (among those listed in Table 1) is best fit to simulate precipitation and temperature changes in Ethiopia? This can be answered by comparing model output with actual observations and was the main objective of this paper.

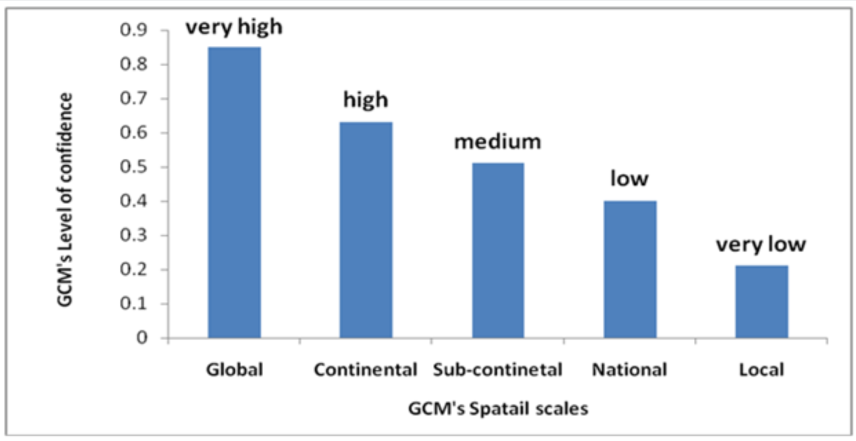

Figure 1: Spatial variation in the confidence levels of GCMs.

Table 1: The 16 GCMs selected for simulation of future precipitation and temperature for Ethiopia.

Model Name	Institution that Designed the Model
csiro_mk3_6_0	Commonwealth Scientific and Industrial Research Organization-mk3.6.0 climate model
fio_esm	The First Institute Oceanography Earth System Model
gfdl_cm3	Geophysical Fluid Dynamics Laboratory climate model, version 3
gfdl_esm2m	Geophysical Fluid Dynamics Laboratory- coupled carbon-climate Earth System Model
bcc_csm1_1	Beijing Climate Centre Climate System Mode, version 1.1
bcc_csm1_1_m	Beijing Climate Centre Climate System Mode, version 1.1 (moderate resolution)
noresm1_m	Norwegian Earth System Model 1 - medium resolution
giss_e2_h	NASA Goddard Institute for Space Studies E2-H Model
giss_e2_r	NASA Goddard Institute for Space Studies E2-R Model
ipsl_cm5a_mr	Institute Pierre Simon Laplace Model CM5A-MR
mri_cgcm3	Meteorological Research Institute Coupled Global Climate Model Version 3
miroc_esm	Model for Interdisciplinary Research on Climate-Earth System Model
miroc_esm_chem	An atmospheric chemistry coupled version of MIROC-ESM
miroc5	Model for Interdisciplinary Research on Climate
ccsm4	Community Climate System Model, version 4
cesm1_cam5	Community Climate System Model, version1-Community Atmospheric Model, version 5

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Material and Methods

Climate and geography

Ethiopia is a country in East Africa where climate change impacts and vulnerabilities are greatest (Figure 2). This is exacerbated by high dependence on rain fed agriculture and lower affluence of the nation. Ethiopia has two rainy seasons: the kiremt, which mostly extend from June to September, is the major rainy season in most parts of the country and responsible for major crop production. The belg rain season, March to April, is the shorter rain season used for minor crop production. In current times, as a result of climate change, these rain seasons are becoming inconsistent with respect to the onset, ending, distribution and amount of rainfall. Three things do matter to affect climate variation in Ethiopia. The first is the seasonal movement of the Intertropical Convergence Zone (ITCZ) to north in July and south in January. The second is the atmospheric circulation associated with ITCZ, and finally, the complex topography with marked contrast in elevation. Broadly, Ethiopia's climate is categorized into

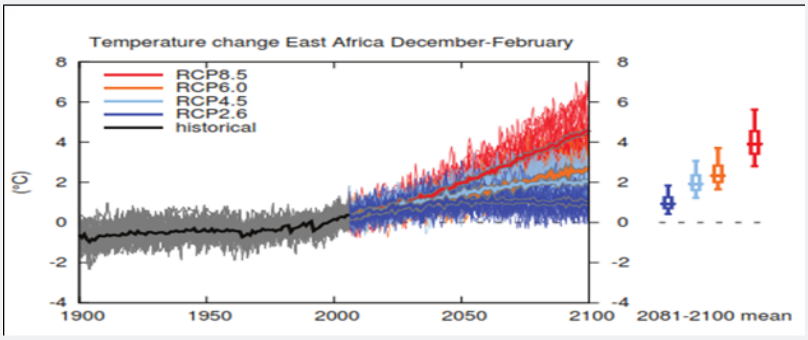

Figure 2: Temperature changes in East Africa for December to February with the darker line showing the historical trend and the scale bars at the right indicate mean of the period 2081-2000 (Source 1).

(i) Alpine vegetated cool zone (locally Dega) with temperature ranging from near freezing to 16°C, precipitation from 1270 -1280mm and altitude over 2600m a.s.l;

(ii) Temperate climate (locally woina dega) with temperature ranging from 16-30°C, precipitation from 510 -1530mm and altitude 1500-2500m a.s.l;

(iii) Hot tropical and arid zone (locally kola) with temperature ranging from 27-50°C, precipitation at most 510mm and altitude below 1500m a.s.l.

These large physiographic variabilities of Ethiopia combined with large climate variability observed in the 20th century, has made climate change projections in Ethiopia very challenging [14,15]. The country has experienced high degree of variability in rainfall and an increase in temperature as indicated by observed climate trends [16]. These changes are expected to continue in the future and thereby having impacts on food production, water availability, gender differentials, human migration, health and the economy of the nation as a whole [17]. Risks from climate change (amplified and emerging risks) are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development, especially in less developed countries [1].

Geographically, Ethiopia has a varying landscape ranging from as low as -120m below sea level at the Dallol depression in the northeast to as high as 4620m above sea level at the Mountain Ras Dashen in the northern part. There is high dynamics in the state of these ranges of fragile landscapes in Ethiopia due to large scale deforestation and environmental degradation which in turn influence the climate by their effects on evapotranspiration and surface albedo. Evaluation of climate models based on past climate observations considered in this paper reveals the need for climate models to signify the observed behaviour of past climate as a necessary condition to be considered a viable tool for future projections [1].

Data source and method

In this analysis, the representative concentration pathway 6.2 (RCP6.2: medium-high emission) data by World Bank Group for Ethiopia was used. RCP6.2 was developed by the AIM modelling team at the National Institute for Environmental Studies (NIES) in Japan. It is a stabilization scenario in which total radiative forcing (6.2W/m2) is stabilized shortly after 2100, without overshoot, by the application of a range of technologies and strategies for reducing GHG emission. It defines a CO2 equivalent to 850ppm, temperature anomaly 3°C, a pathway of stabilization without overshoot and special report on emissions scenarios (SRES) temperature anomaly equivalent SERS B2 [18-23].

The basic foundation for global and regional climate change projections are the observed climate and recent climate change. Historical and projected open data of precipitation and temperature from World Bank group for Ethiopia for RCP6.2 were used [24]. The variables of interest were mean monthly precipitation and temperature. The base period for historical observation is 1986-2005 and the periods for future projection are 2020-2039, 2040-2059, 2060-2079 and 2080-2099. The observed mean monthly precipitation and temperature for the

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period 1986-2005 was correlated to the projected mean monthly precipitation and temperatures of each of the 16 GCMs for each future period to evaluate the optimum GCM performance to simulate Ethiopia's climate. The correlation coefficient (R2) has been used to indicate how capable each model is to replicate the mean monthly precipitation and temperature data for the period 1986-2005. A higher value of R2 shows that a particular GCM has replicated the historical data in its future simulation while a value near zero did not replicate the historical data and is not suitable for projecting Ethiopia's future climate when used independently.

Results and Discussions

Temperature and precipitation anomalies

Based on observed climate data of 1986-2005 as a baseline (Figure 3), there is significant variation in precipitation projections among the GCMs in all the four periods. Among the 16 GCMs, 6 have yielded a decrease of precipitation in 2040-2059 as compared to that in 2020-2039, while the remaining 10 GCMs have yielded the opposite (Figure 4). The standard deviations for precipitation between the models for the periods 2020-2039, 2040-2059, 2060-2079 and 2080-2099 are 324.20, 320.38, 317.61 and 332.70, respectively. GCMs cesm1_cam5, csiro_mk3_6_0, fio_esm, gfdl_cm3, gfdl_esm2m, bcc_csm1_1, bcc_csm1_1_m, ccsm4 and noresm1_m have projected moderately; while GCMs such as giss_e2_h, giss_e2_r, ipsl_cm5a_mr and mri_cgcm3 have resulted in lower precipitation projections. GCMs miroc_esm, miroc_esm_chem and miroc5 have resulted in higher precipitation projections for the indicated periods.

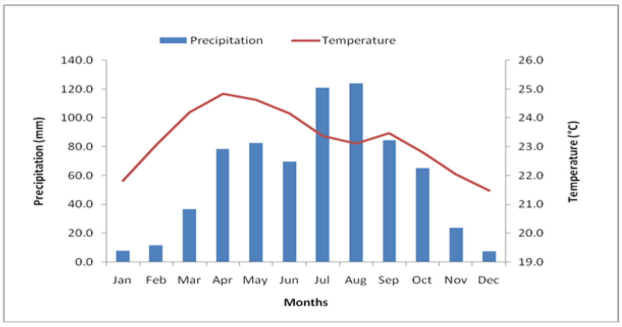

Figure 3: Historical observed monthly precipitation and temperature for Ethiopia for 1986-2005.

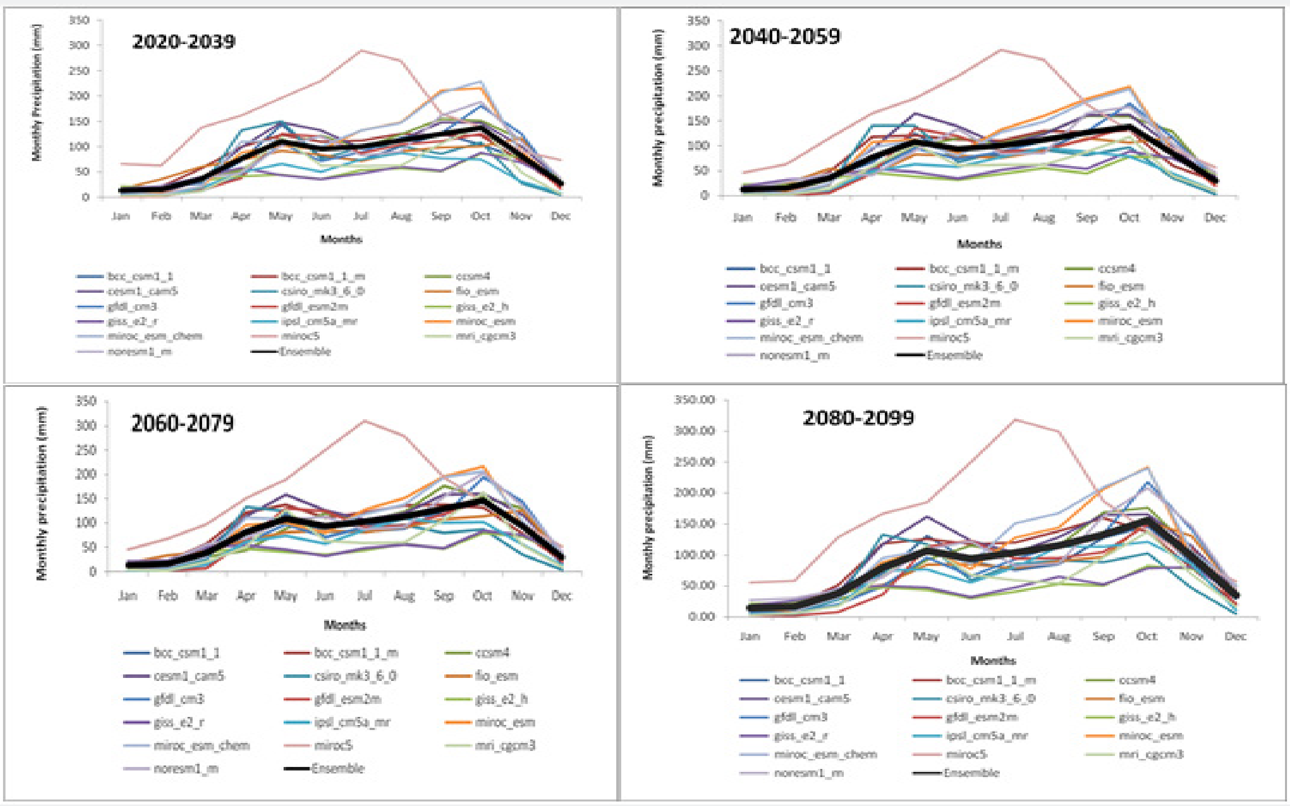

Figure 4: Precipitation estimate by GCMs for Ethiopia for different periods for medium-high emission scenario.

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Regarding temperature projections, there is no significant variation among the models' estimates in 2020-2039, 2040-2059, 2060-2079 and 2080-2099. All the sixteen models including their ensemble showed an increase of temperature in the periods that precede it (Figure 5). The standard deviations of the mean for the consecutive periods are 0.85, 0.87, 0.90 and 0.92 respectively.

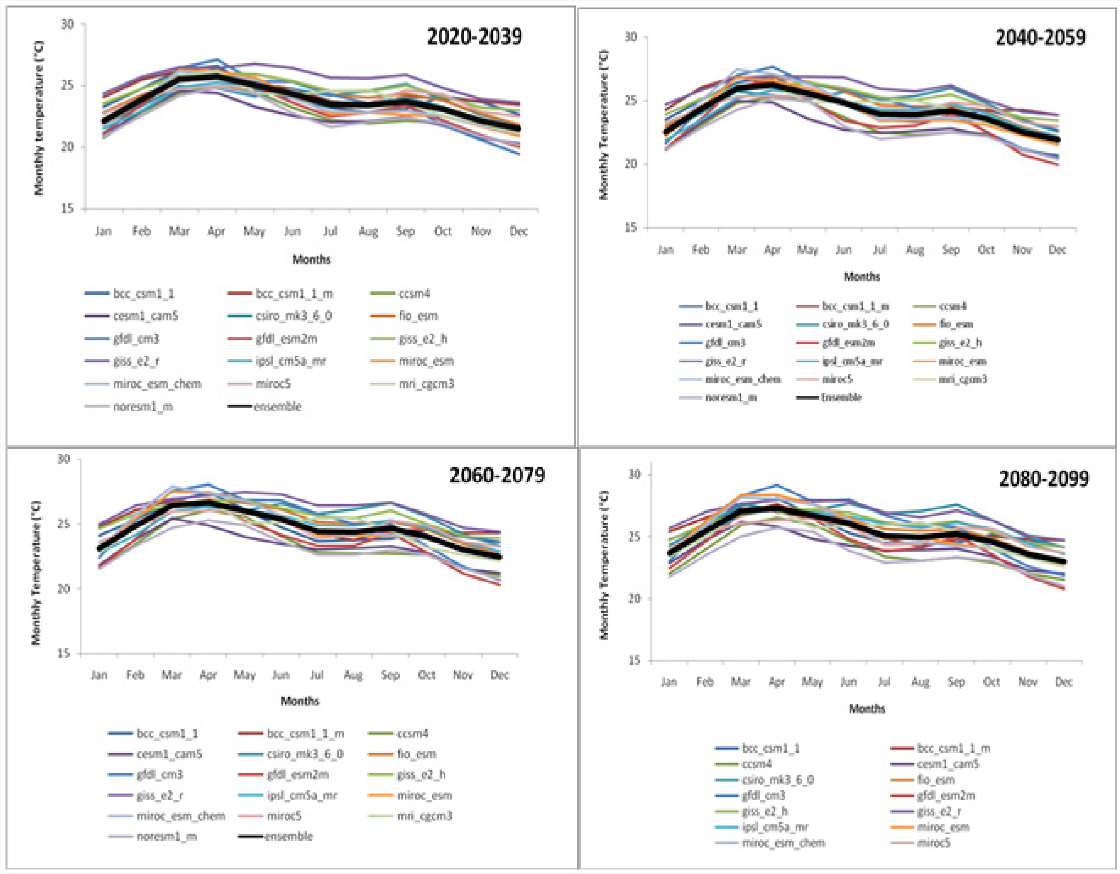

Figure 5: Temperature estimate by GCMs for Ethiopia for different periods for medium-high emission scenario.

There is significant variation among the models in projection of precipitation in different period for Ethiopia with coefficient of variation 34%. The variation in temperature projection among the models is minimal with coefficient of variation about 4% (Table 2 & Figure 6). This showed that projections of changes in temperature are more reliable than those in precipitation. The coefficient of variation for the model projection is more than three times higher than observed for temperature and more than thirty times higher than observed for precipitation. This in turn showed that how much the global climate models uncertain are.

Table 2: Variation in the projection of precipitation and temperature by different GCMs for medium-high emission scenario for Ethiopia.

Variables	Variation among the 16 GCMs and Base Period		
	Annual Mean	Standard Deviation	Coefficient of Variation (%)
Temperature 1986-2005	**23.25°C**	**0.26**	**1.13**
Temperature 2020-2039	23.65°C	0.85	3.59
Temperature 2040-2059	24.13°C	0.87	3.61
Temperature 2060-2079	24.62°C	0.9	3.66
Temperature 2080-2099	25.21°C	0.92	3.65
Precipitation 1986-2005	**714.12mm**	**40.29**	**5.64**
Precipitation 2020-2039	934.78mm	324.2	34.68
Precipitation 2040-2059	931.57mm	320.38	34.39
Precipitation 2060-2079	964.88mm	317.61	32.92
Precipitation 2080-2099	988.41mm	332.7	33.66

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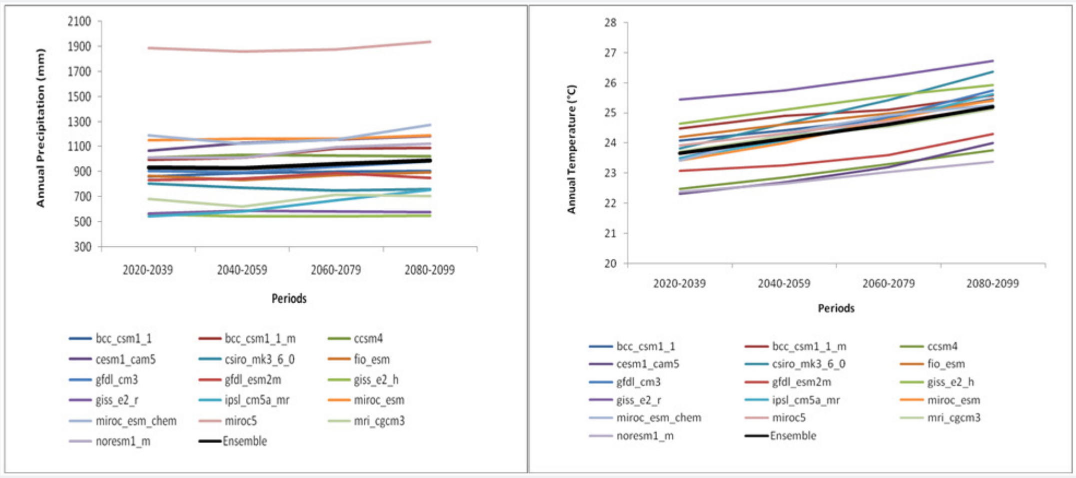

Figure 6: Annual precipitation and temperature projection by GCMs for different models for the medium-high emission scenario for Ethiopia.

When precipitation in the period 2080-2099 compared to the periods 2060-2079, 2040-2059 and 2020-2039, it will increase, on average, by 23.53mm, 56.85mm and 53.63mm, respectively. That in the period 2060-2079 is compared to the periods 2040-2059 and 2020-2039, it will also increase, on average, by 33.31mm and 30.10mm, respectively. However, the precipitation in the period 2040-2059 will decrease by 3.22mm as compared to the period 2020-2039 (Table 3). In the case of temperature, the period 2080-2099 will show an increase of 0.59°C, 1.07°C and 1.55°C over the periods 2060-2079, 2040-2059 and 2020-2039, respectively. The temperature in the period 2060-2079 will also show an increase of 0.48°C and 0.97°C over the periods 2040-2059 and 2020-2039, respectively. The temperature in the period 2040-2059 will also increase by 0.48°C as compared to the period 2020-2039 (Table 4.

Table 3: Temperature differences between periods by different GCMs for medium-high emission scenario for Ethiopia.

GCMs Precipitation (mm)	Precipitation Differences					
	(2080-2099) - (2060-2079)	(2080-2099) - (2040-2059)	(2080-2099) - (2020-2039)	(2060-2079)- (2040-2059)	(2060-2079) - (2020-2039)	(2040-2059)- (2020-2039)
bcc_csm1_1	3.04	15.29	43.22	12.25	40.18	27.93
bcc_csm1_1_m	6.6	82.06	96.98	75.47	90.38	14.91
ccsm4	-5.5	-11.91	9.06	-6.41	14.55	20.96
cesm1_cam5	26.43	58.95	119.56	32.52	93.14	60.61
csiro_mk3_6_0	10.91	-9.54	-44.86	-20.45	-55.78	-35.32
fio_esm	21.38	61.31	27.01	39.94	5.63	-34.3
gfdl_cm3	44.18	88.4	78.65	44.22	34.47	-9.75
gfdl_esm2m	-39.08	4.1	19.27	43.18	58.36	15.18
giss_e2_h	10.04	10.46	-8.12	0.42	-18.17	-18.59
giss_e2_r	-3.11	-11.64	9.29	-8.53	12.4	20.93
ipsl_cm5a_mr	83.43	172.76	209.87	89.33	126.44	37.1
miroc_esm	26.93	27.02	35.46	0.09	8.53	8.44
miroc_esm_chem	115.07	149.65	78.23	34.58	-36.84	-71.42
miroc5	58.67	76.23	49.31	17.56	-9.36	-26.92
mri_cgcm3	-11.32	86.21	26.17	97.54	37.49	-60.04
noresm1_m	28.84	110.17	108.94	81.33	80.1	-1.23
Ensemble	23.53	56.85	53.63	33.31	30.1	-3.22

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Table 4: Temperature differences between periods by different GCMs for medium-high emission scenario for Ethiopia.

GCMs-Temperature (°C)	Temperature Differences					
	(2080-2099)-(2060-2079)	(2080-2099)-(2040-2059)	(2080-2099) -(2020-2039)	(2060-2079)-(2040-2059)	(2060-2079) -(2020-2039)	(2040-2059)-(2020-2039)
bcc_csm1_1	0.63	1.04	1.37	0.4	0.74	0.33
bcc_csm1_1_m	0.5	0.69	1.1	0.19	0.61	0.42
ccsm4	0.46	0.9	1.27	0.44	0.81	0.37
cesm1_cam5	0.8	1.3	1.68	0.5	0.88	0.38
csiro_mk3_6_0	0.94	1.74	2.55	0.79	1.61	0.82
fio_esm	0.4	0.78	1.2	0.38	0.8	0.42
gfdl_cm3	0.88	1.49	2.25	0.6	1.37	0.77
gfdl_esm2m	0.72	1.06	1.24	0.34	0.52	0.18
giss_e2_h	0.35	0.82	1.28	0.46	0.93	0.47
giss_e2_r	0.51	0.99	1.27	0.48	0.76	0.28
ipsl_cm5a_mr	0.86	1.55	2.14	0.68	1.28	0.59
miroc_esm	0.65	1.42	2.02	0.78	1.37	0.59
miroc_esm_chem	0.35	0.95	1.85	0.6	1.5	0.91
miroc5	0.43	0.84	1.24	0.41	0.8	0.4
mri_cgcm3	0.58	0.89	1.4	0.31	0.82	0.51
noresm1_m	0.33	0.72	1.01	0.39	0.67	0.29
Ensemble	0.59	1.07	1.55	0.48	0.97	0.48

Replication of the observed climate by the GCMs

The application of the correlation methods of the observed temperatures and precipitation for the base period 1986-2005 with that of the GCMs for medium-high emission scenario showed that, for Ethiopia, temperatures are better replicated by almost by all 16 GCMs than precipitation through the different periods. In relative terms, precipitation in Ethiopia has been better replicated by models bcc_csm1_1_m, ipsl_cm5a_mr and miroc5 while poorly replicated by models giss_e2_h, giss_e2_r, noresm1_m, fio_esm and gfdl_cm3 (Figure 7 & Table 5). Temperatures are best replicated by models fio_esm, giss_e2_h, ipsl_cm5a_mr and gfdl_cm3. It is poorly replicated by model's bcc_csm1_1 and bcc_csm1_1_m. Among the 16 GCMs considered in this analysis for medium-high emission, the model ipsl_cm5a_mr was found to better replicate both temperatures and precipitations within the different periods with that of the observed temperatures and precipitations in the base period 1986-2005.

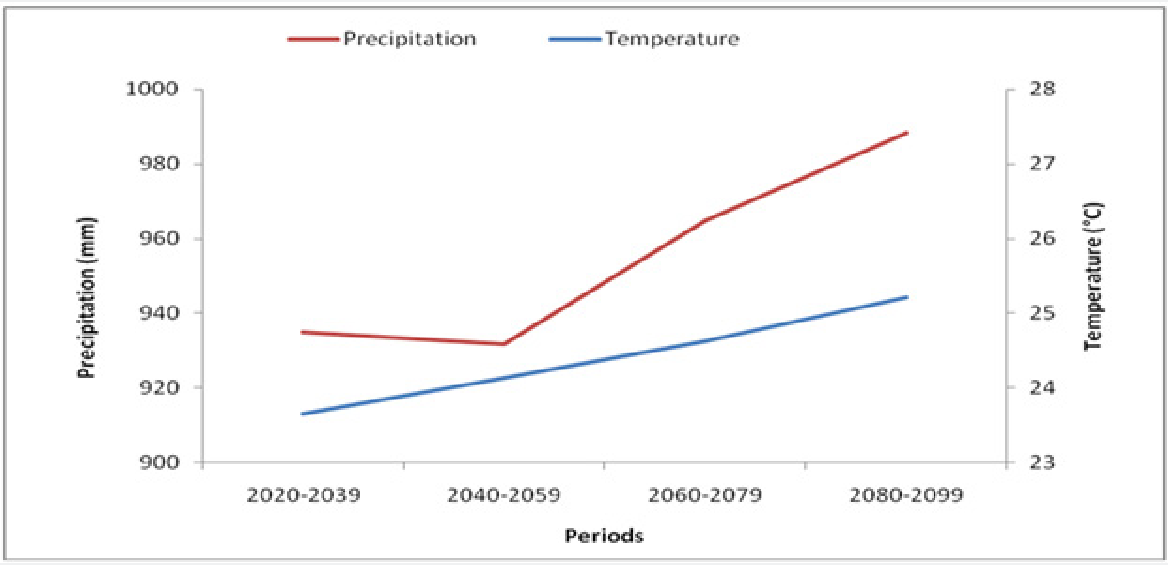

Figure 7: Simulated future climate trends for Ethiopia for different periods for medium-high emission scenario.

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Table 5: Correlation of monthly temperature and precipitation projected by different GCMs for medium-high emission with that of the 1986-2005 observation for Ethiopia.

Model	Correlation (R2) with 1986-2005 Observation-Monthly							
	2020-2039		2040-2059		2060-2079		2080-2099	
	Prep	Temp	Prep	Temp	Prep	Temp	Prep	Temp
bcc_csm1_1	0.52	0.49	0.42	0.67	0.41	0.55	0.36	0.56
bcc_csm1_1_m	0.79	0.52	0.77	0.48	0.78	0.45	0.75	0.41
ccsm4	0.43	0.93	0.4	0.93	0.35	0.9	0.34	0.92
cesm1_cam5	0.51	0.82	0.51	0.8	0.5	0.81	0.5	0.8
csiro_mk3_6_0	0.68	0.73	0.63	0.72	0.71	0.76	0.65	0.78
fio_esm	0.32	0.98	0.28	0.99	0.29	0.99	0.18	0.99
gfdl_cm3	0.32	0.93	0.31	0.94	0.25	0.94	0.21	0.95
gfdl_esm2m	0.48	0.9	0.43	0.88	0.44	0.9	0.35	0.91
giss_e2_h	0.14	0.96	0.06	0.97	0.12	0.94	0.04	0.97
giss_e2_r	0.2	0.92	0.17	0.93	0.09	0.93	0.13	0.94
ipsl_cm5a_mr	0.86	0.97	0.8	0.94	0.75	0.95	0.57	0.94
miroc_esm	0.5	0.85	0.55	0.87	0.48	0.85	0.41	0.83
miroc_esm_chem	0.51	0.85	0.53	0.82	0.47	0.82	0.48	0.82
miroc5	0.89	0.85	0.91	0.85	0.89	0.84	0.9	0.78
mri_cgcm3	0.37	0.82	0.48	0.84	0.29	0.79	0.3	0.82
noresm1_m	0.23	0.9	0.2	0.89	0.2	0.93	0.13	0.93
Ensemble	0.62	0.94	0.61	0.94	0.57	0.94	0.52	0.95

As in Figure 7, the trend line for precipitation is y = 19.42x + 906.30 (R2 = 0.868) and that of temperature is y = 0.517x + 23.11 (R2 = 0.997), where y is predictable precipitation or temperature; (x = 1, 2, 3, 4 each representing the respective periods). That means, in the medium-high emission scenario, precipitation and temperatures will increase on average by 19.42mm and 0.517°C, respectively, over each 2 decades.

Conclusion

Although there are uncertainties in climate change prediction with respect to timing, direction, variability and extreme events, the GCMs are remained important tools to predict future climate and help to plan adaptation actions. The 16 GCMs treated in this analysis for medium-high emission scenario have produced significant variation in precipitation projection with higher standard deviation between the models for Ethiopia. On the other hand, the variation is non-significant, and the standard deviation is very small in the case of temperature projection for Ethiopia. This in turn indicated that the 16 GCMs are better suited to project temperature for Ethiopia than precipitation. The GCMs miroc5 and fio_esm were found to better replicate the observed precipitation and temperature, respectively, of the period 1985-2005 for Ethiopia. This means, these models are relatively better to predict Ethiopia's climate in the furfure as compared to the other 14 GCMs computed in this analysis for the medium-high emission scenario. Nonetheless, what to be recommended is that to use the ensemble average in order to optimize the large uncertainty that might be created by being using a single model.

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How to cite this article: Zenebe Mekonnen. Precipitation and Temperature Projections for Medium-High Emission Scenario by General Circulation Models for Ethiopia. Int J Environ Sci Nat Res. 2020; 23(4): 556119. DOI: 10.19080/IJESNR.2020.23.556119

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