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Climatic projections of Western India using global and regional climate models

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ABSTRACT

This research work aimed to project and analyze climatic variability using GCMs and RCMs in the Hathmati River Basin, which happens to be one of the most important tributaries of Western India. The analysis included a baseline period from 1980 to 2014 and a future scenario (2050s) under a representative concentration pathway (RCP4.5). Following the evaluation of bias correction methods, distribution mapping and power transformation were used for temperature and precipitation projection, respectively. The 2050 s RCP4.5 simulations showed an increase in precipitation to 1,015.54 mm from 936.91 mm giving around a 8.45% increase in average precipitation. For temperature, the maximum temperature was around a 7.05% increase taking the average temperature to 34.21 from 33.97. The minimum temperature was 20.24 from 20.41 showing a positive change of around 8.4%. The future precipitation and temperature change projected might worsen the water stress and increase the probability of the occurrence of severe events, and hence mitigation strategies and management options to reduce this negative impact should be encouraged.

Key words: climatic models, GCM, Hathmati, RCP, simulation

HIGHLIGHTS

- Work is on one of the most important tributaries of Western India.
- Includes latest technology and method.
- GCMs are used.
- RCP4.5 projections are used for forecasting.
- BIAS correction is incorporated.

LIST OF ABBREVIATIONS

Avg.	Average
GIS	Geographical Information System
ha	Hectare
hr	Hour
IRS	Indian Remote Sensing Satellites
km	Kilometer
LISS II	Linear Imaging Self-scanning Sensor II
m	Meter
max	Maximum
min	Minimum
mm	Millimeter
PCP	Precipitation
Sc	Scenario
TMP	Temperature
CMIP5	Coupled Model Intercomparison Project-5
RCP 4.5	Representative Concentration Pathway

INTRODUCTION

The basic aim of this work was to find the existing climatic variabilities in the study area and project them using general circulation models (GCMs). The projections were performed using RCP4.5 but the work could be extended in the near future by considering some other projections. The Hathmati River was chosen as it is one of the most important tributaries of Western India (Shaikh *et al.* 2021). The Hathmati River was taken to demonstrate the work but it is not limited to this particular region. In the future the work could be extended by considering other similar tributaries.

GCMs have become the most reliable and widely applicable way to assess climate change and forecast climate scenes in inter-decadal studies. Climate predictions in the five Intergovernmental Panel on Climate Change (IPCC) Assessment Reports are all based on GCMs (Zhang *et al.* 2017). Projecting climate change and its impacts on surface runoff are essential for allocation and scheduling of water resources, and researchers have conducted much significant work in recent years, basically following the pattern of a future climate scenario design hydrological model-impact assessment. The hydrological model makes it possible to obtain more potential changes and detailed information on various climatic characteristics of the catchment by predicting surface runoff and providing continuous simulations of daily and monthly runoffs (Song *et al.* 2022). The impact of climate change on the water cycle is the result of the interaction between climate variables, which are highly correlated with one another. Climate models offer tools for reproducing and anticipating climate (Dakhlaoui & Djebbi 2021). Island nations are more vulnerable to the impact than the land masses (Perera *et al.* 2020). Climate models, called GCMs, are used to project the potential climate change for assumed future greenhouse gas emission scenarios. The long time scales and uncertainty due to global change have led analysts to develop 'scenarios' of future environmental, social, and economic changes to improve the understanding among decision-makers of the potential consequences of their decisions (Rouhani & Jafarzadeh 2018). More often there is a reliance on a physical/statistical relationship established in the historical climate that is transferable in the future climate change scenarios to predict future changes in water distribution (Ibebuchi 2021). Due to the impact of global warming, glacier and snow ablation in the basin accelerates, runoff in the downstream replenishment increases, and hydrological events, such as floods and droughts, occur. Hydrological models serve as an important tool for studying stream flow processes at the watershed scale (Xiang *et al.* 2022). Scale interactions between large-scale atmospheric modes of variability can be modelled without artificial boundaries introduced when a large-scale GCM provides boundary conditions for a regional climate model (Muetzelfeldt *et al.* 2021). In statistical bias correction, a statistical relationship between the modelled and the observed variables is established over the historical period, and the constructed relationship is then used for bias correction of the modelled projection (Dutta & Bhattacharjya 2022). Recently, the changes in the frequency and intensity of extreme events have led to severe climate-related disasters across many parts of the world. These extreme events (i.e., floods, droughts, and heat waves) have gained considerable attention from climate scientists and the general public due to their devastating impact on the ecosystem and different sectors of the economy (Ayugi *et al.* 2020). There is a large amount of uncertainty associated with future projections when GCMs data are used as the input for hydrological models. The hydrological models are classified based on the degree of complexity in conceptualizing the catchment scale hydrological processes and scale of application (Padhiary *et al.* 2020). The impacts of global warming on the hydrological cycle and water resource systems have been an important concern worldwide in recent years. Various GCM-based simulations, studies and experiments have projected an increase in temperature due to the enhanced levels of greenhouse gases. Consequently, climate processes are expected to intensify, leading to severe impacts on agricultural and energy production, ecosystems, water availability, heat waves, waterlogging, flooding and drought. Statistical downscaling, a data-driven technique, substantially reduces the computational resources and can be used at the region of interest if sufficient data are available to build the statistical model (Hengade *et al.* 2018). GCMs are the major tools that provide information about the future climate. Generally speaking, there are two steps to follow to quantify the hydrological impacts of climate change based on GCMs outputs: (1) GCM outputs (usually precipitation and temperatures) are first downscaled to a watershed or to a site-specific scale to obtain climate change projections at an appropriate scale; and (2) climate change projections are then input into hydrological models to simulate future hydrological conditions (Chen *et al.* 2011). GCMs are the main tools used nowadays to simulate the evolution of the climate system globally (Usman *et al.* 2021). The spatial resolution of a GCM is very large and may not be compatible with hydrological models (sensitive to regional or local variations). Hence, various downscaling methods are used. Representative concentration pathways (RCPs) indicate possible future emission scenarios. RCPs have been developed by the Coupled Model Inter-comparison Project Phase 5 (CMIP5) and are considered a sound approach for developing mitigation plans and also for analyzing the impacts of climate change (Mishra *et al.* 2021). Statistical downscaling and bias correction approaches primarily rely on hydrometeorological observations over a historical reference period. It is, therefore, primordially important that the observed reference dataset represents the true climate state as closely as possible (Tarek *et al.* 2021). As the reference data without external forcing are not available for most of the hydrometeorological variables, GCMs are the best tools that provide climate data taking into consideration with or without different forcings. GCMs are generally used to study the past, present, or future climate (Sharma *et al.* 2021). These processes are represented by parameterization schemes, which relate unresolved quantities such as cloud statistics to variables resolved on the climate models' computational grid, such as temperature and humidity. The parameterization schemes depend on parameters that are previously unknown, and so fixing the parameters is associated with uncertainty (Dunbar *et al.* 2021).

Case study and data

The Hathmati River watershed (23°30′49″N 72°49′29″E) has been selected for the study and the location map is shown in Figure 1. The Hathmati is one of the major tributaries (left) of the Sabarmati River (Western India). The spatial variation in the rainfall is highest for the Hathmati basin amongst all the sub-basins of the Sabarmati basin (Dave *et al.* 2012). It lies in Bhiloda (Sabarkantha district) and rises from the Gujarat Malwa Hills. After travelling along a course at 98 km it meets Sabarmati near the village Ged. The total catchment area is 1,574 km^2 (157,400 ha). The rain gauge station is installed at Bhiloda where the average annual rainfall is recorded as 864 mm. The coefficient of variation of annual rainfall over the basin is rather high and ranges between 42 and 65% and the average maximum and minimum temperatures reach about 38 °C and 16 °C (Dave *et al.* 2012), respectively. The data for the study include various spatial data such as DEM, LULC, Soil Map generated from CARTOSAT-I, SRTM, BHUVAN and IRS~ID LISS III satellite data and prepared in ArcGIS on 1:12500 scale with the resolution of 30 m; several collateral data such as weather files (from 1966 to 2015) from rain gauge stations and climate stations were collected.

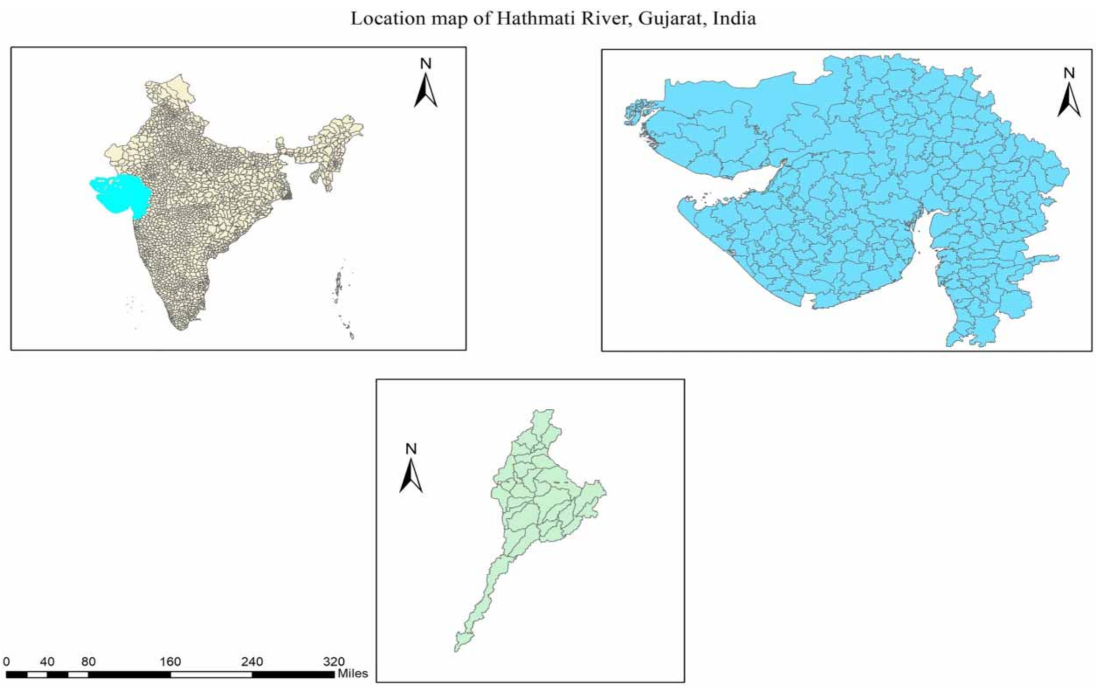

Figure 1 | Location map of Hathmati River, Gujarat, India.

SIMULATION USING GCMS

The future climate is predicted to be debatable and can severely affect the water resources around the world (Khaniya *et al.* 2020). Quantifying the effects of climate change on hydrological processes and runoffs are very important for water resources management and are helpful for decision-makers to develop adaptations to climate change (Wen *et al.* 2021). Most GCM simulations at present are performed at relatively coarse horizontal resolutions (~1°) due to the tremendous computational cost required to run them at finer resolutions. While hydrological processes have been widely investigated and have significant impacts on other Earth system processes, GCMs are seldom applied to study hydrological processes, because their coarse resolution inhibits reliable watershed scale analyzes (Xu & Di Vittorio *et al.* 2021). Mapping possible changes in the climatic parameters is crucial for planning climate change adaptation and mitigation strategies. This is particularly important in environmentally critical locations, where subtle changes in weather parameters may significantly impact the service sector (Hamed *et al.* 2022). The principal tools for the assessment of climate change projections of drought regimes are the global climate models and regional climate models (Dixit *et al.* 2021). GCMs represent the numerous atmospheric processes of the global climate system and are the main tools for estimating future climate patterns and studying the changes in precipitation and temperature patterns. The various GCMs are continuously improved to enable the output to be used for different climate change studies in the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Pradhan *et al.* 2021). To better understand past, present, and future climate changes, the Working Group on Coupled Modeling under the framework of the World Climate Research Programme (WCRP) established the Coupled Model Intercomparison Project (CMIP3, CMIP5, and now CMIP6) (Supharatid & Nafung 2021). Watershed models are often used to simulate the impact of future climate conditions on hydrologic processes. However, Teutschbein & Seibert (2012) stated that simulations of temperature and precipitation often show significant biases due to systematic model errors or discretization and spatial averaging within grid cells, which hampers the use of simulated climate data as direct input data for hydrological models. Bias correction procedures are used to minimize the discrepancy between observed and simulated climate variables on a daily time step so that hydrological simulations driven by corrected simulated climate data match reasonably well the simulations using observed climate data. In this study the coupled model interpretation program (CMIP-5) has been used to generate forecasting scenarios. The tool used for this task was CMhyd (Climate Model data for hydrologic modelling) which is available in the public domain. CMhyd is a tool that can be used to extract and bias-correct (downscale) data obtained from global and regional climate models. The selection of the model is carried out as per the recommendations of Jena *et al.* (2015). Their study shows that four models, CCSM4, CESM1-CAM5, GFDL-CM3, and GFDL-ESM2G, best captured the pattern in Indian summer monsoon rainfall over the historical period (1871–2005). For assessing the present and future climate change scenarios, daily maximum temperatures from the CMIP5 climate model historical simulations and projections based on the Representative Concentration Pathways (RCP4.5) scenario (Taylor *et al.* 2012) were also used. The whole process of this simulation can be summarised as:

1. Find the existing anomalies between historical observed data and modelled data (CMIP5).
2. Perform the bias correction using CMhyd tool to minimize the anomalies for all the selected models.
3. Select the model showing the best fit or minimum anomalies.
4. Construct the future projections based on this model using Representative Concentration Pathways (RCP4.5) scenario.

From an extensive literature review a selection of models was made and the details of the models used are shown in Table 1. All the models were compared using the historical observed data and the bias correction was performed using CMhyd tool which is available in a public domain. The results of the comparison of all the four models with the observed historical data after the bias correction showed that CCSM4 was the most efficient model. The comparison of this model with the observed data is shown in Figures 2 and 3 and the future projections obtained from this model were used as input data for the model.

Table 1 | Details of CMIP5 models considered for the study

Sr. no.	Model (Lat° × Long°)	Modelling centre (Group)	RMSE
1	CCSM4 (1.25 × 0.9424)	National Center for Atmospheric Research, USA	0.74
2	CESM1-CAM5 (1.25 × 0.9424)	Community Earth System Model Contributors, NCAR USA	0.59
3	GFDL-CM3 (2.5 × 2)	NOAA Geophysical Fluid Dynamics Laboratory	–
4	GFDL-ESM2G (2.5 × 1.5169)	NOAA Geophysical Fluid Dynamics Laboratory	–

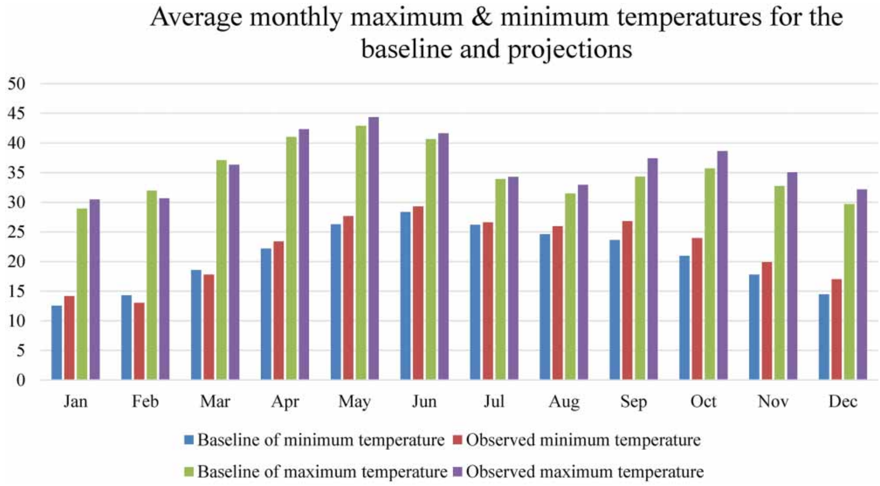

Figure 2 | Average monthly maximum and minimum temperatures for the baseline and projections.

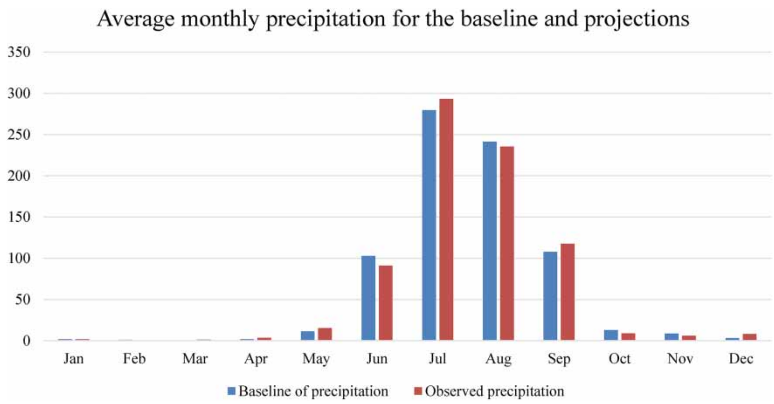

Figure 3 | Average monthly precipitation for the baseline and projections.

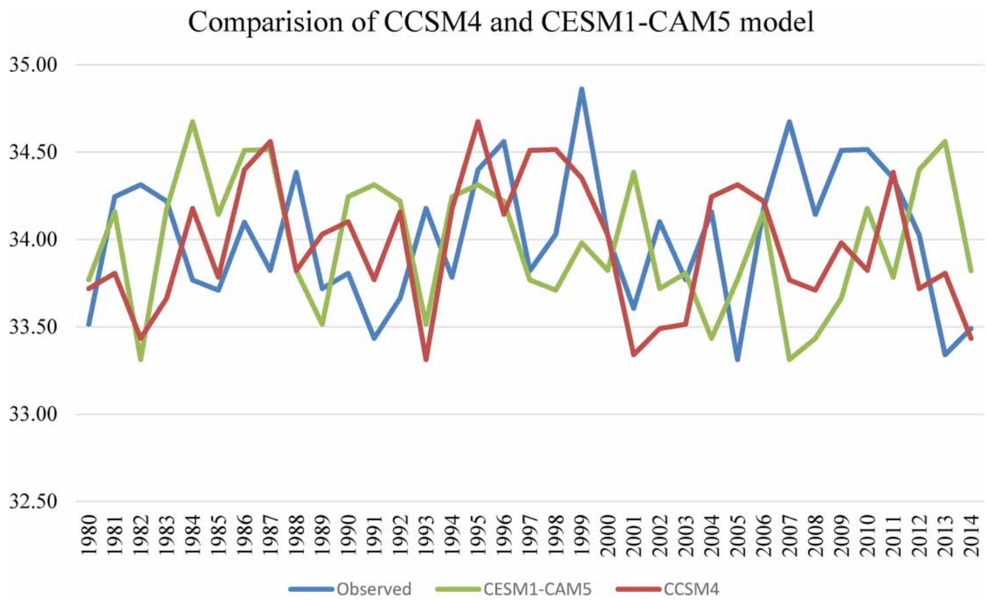

Figure 4 | Comparison of CCSM4 and CESM1-CAM5 model for efficiency.

RESULTS AND DISCUSSION

The objective was served by using CMIP5 project database and the models used for the watershed are shown in Table 1. From the extensive literature survey on the CMIP5 models, two models namely CCSM4 and CESM1-CAM5 were selected to process the bias correction. As shown in Figure 4 both models were compared after implementing the bias correction in the tool CMhyd. From the RMSE score of both the models, CCSM4 is chosen to run the projections. For projections, the RCP 4.5 project was used in which the precipitation and temperature are projected up to 2050 as shown in Figure 5. Following the evaluation of bias correction methods, the distribution mapping and power transformation were used for temperature and precipitation projections,

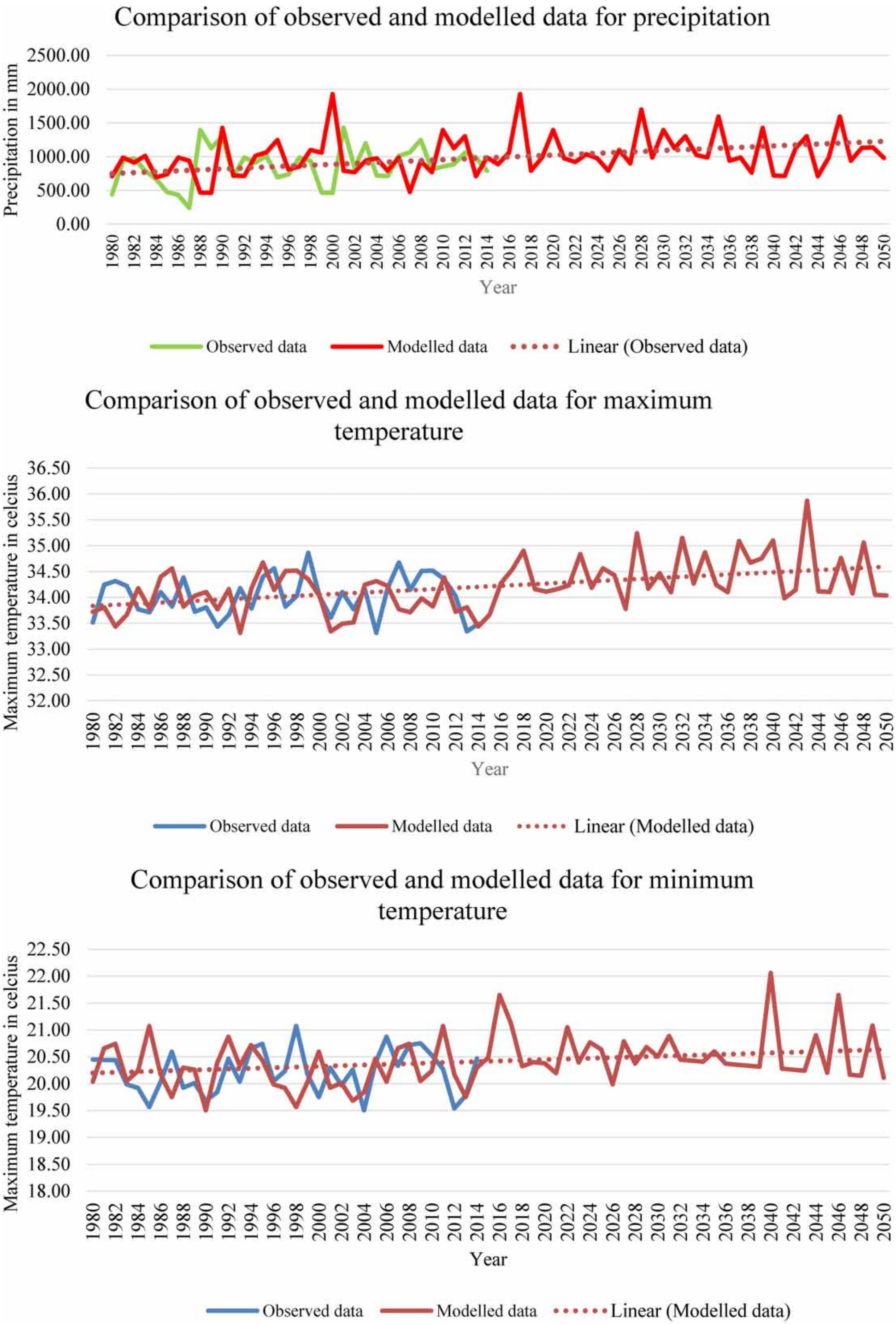

Figure 5 | Comparison of CCSM4 model with observed data along with the RCP-4.5 projections.

respectively. The 2050s RCP4.5 simulations showed an increase in precipitation to 1,015.54 mm from 936.91 mm giving around 8.45% of increase in average precipitation. For temperature, the maximum temperature shows around 7.05% increase taking the average temperature to 34.21 from 33.97. The minimum temperature goes to 20.24 from 20.41 showing positive change of around 8.4%.

CONCLUSIONS

The aim of the study includes:

1. Selection of the most efficient GCM for the said study area.
2. Doing BIAS correction to bring the data from global to regional level.
3. Selection of appropriate projection method/tool.
4. Projecting the data using the RCP.
5. Finding the anomalies in the data that could be mitigated by applying suitable measures.

For demonstration of the work, the Hathmati River that happens to be one of the most important tributaries of Western India was chosen as the study area. The data ranging from 1980 to 2019 were collected from the state weather department and existing trend was determined. The same data were then projected up to the year 2050 using RCP4.5 projections and the GCM used was CCSM4. From the results it was found that all the parameters namely precipitation, minimum temperature and maximum temperature showed a significant increase in the mean value when compared to the baseline. The future precipitation and temperature change projected might worsen the water stress and probability of the occurrence severe events, and hence mitigation strategies and management options to reduce this negative impact should be encouraged. It is also required to make local predictions on climate change and more scenarios on time frames could be taken that will make the study more diverse.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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