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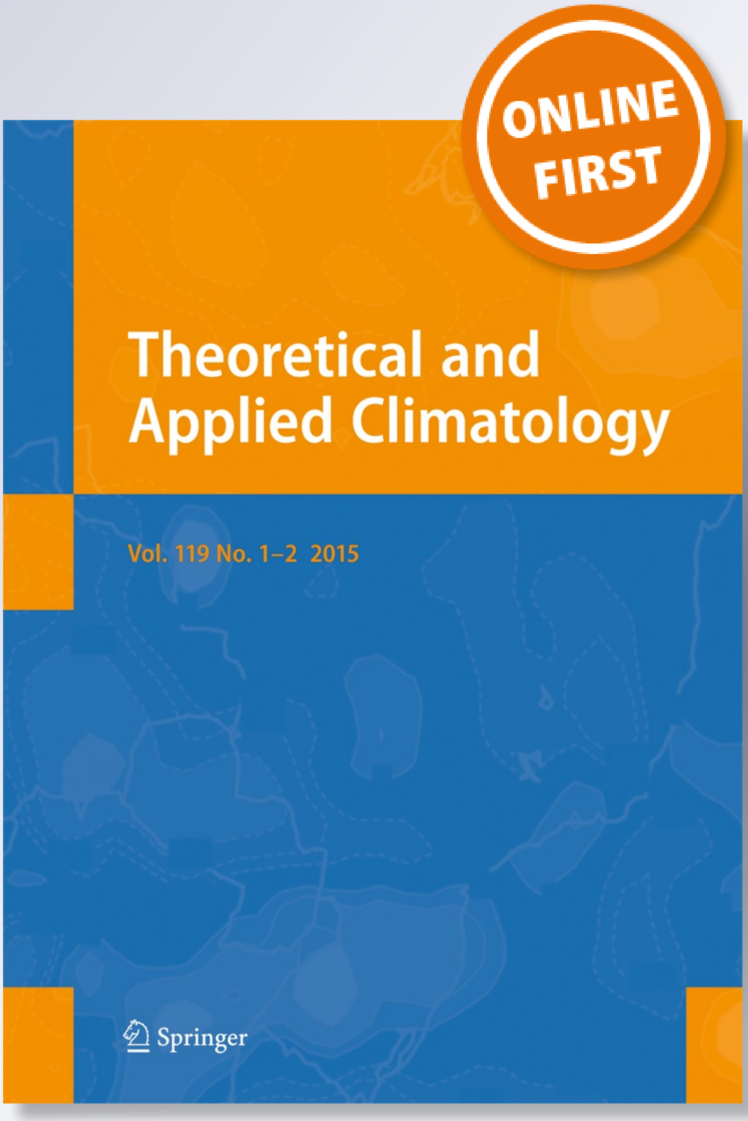

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ORIGINAL PAPER

Climate change projections for Tamil Nadu, India: deriving high-resolution climate data by a downscaling approach using PRECIS

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Abstract In this paper, we present regional climate change projections for the Tamil Nadu state of India, simulated by the Met Office Hadley Centre regional climate model. The model is run at 25 km horizontal resolution driven by lateral boundary conditions generated by a perturbed physical ensemble of 17 simulations produced by a version of Hadley Centre coupled climate model, known as HadCM3Q under A1B scenario. The large scale features of these 17 simulations were evaluated for the target region to choose lateral boundary conditions from six members that represent a range of climate variations over the study region. The regional climate, known as PRECIS, was then run 130 years from 1970. The analyses primarily focus on maximum and minimum temperatures and rainfall over the region. For the Tamil Nadu as a whole, the projections of maximum temperature show an increase of 1.0, 2.2 and 3.1 °C for the periods 2020s (2005–2035), 2050s (2035–2065) and 2080s (2065–2095), respectively, with respect to baseline period (1970–2000). Similarly, the projections of minimum temperature show an increase of 1.1, 2.4 and 3.5 °C, respectively. This increasing trend is statistically significant (Mann-Kendall trend test). The annual rainfall projections for the same periods indicate a general decrease in rainfall of about 2–7, 1–4 and 4–9 %, respectively. However, significant exceptions are noticed over some pockets of western hilly areas and high rainfall areas where increases in rainfall are seen. There are also indications of increasing heavy rainfall events during the northeast monsoon season and a slight decrease during the southwest monsoon season. Such an approach of using climate models may maximize the utility of high-resolution climate change information for impact-adaptation-vulnerability assessments.

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) projects a rise in global average surface temperatures between 1.1 and 2.9 °C by 2100 for a low-emission scenario and between 2.4 and 6.4 °C by 2100 for a high-emission scenario in its fourth assessment report (IPCC 2007). The report by IPCC (2012) indicates that it is likely that the frequency of heavy precipitation events will increase in the 21st century over many areas of the globe. The expected impacts of climate change and the global warming range from changing rainfall pattern to increased salinity of the soil, lack of availability of potable water, inundation of coastal areas by sea water, etc. The major factor which causes concern is the steady increase in temperature and variability in rainfall pattern owing to climate change. Though climate change is a long-term phenomenon, its effect could be slowly and steadily creeping in imperceptibly. Hence, it is very important to develop and plan mitigation and adaptive strategies to address these issues. Advances in climate change modelling now enable best estimates and likely assessed uncertainty ranges for projected warming for different emission scenarios as per IPCC (2007). The coarse horizontal resolution global climate models (GCMs)

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have limitations in capturing the regional orographic features, whereas the high-resolution regional climate models (RCMs) represent the orography better and hence are capable of producing more realistic precipitation climatologies (Kumar et al. 2013). RCMs are limited area models and therefore need to be driven by time-dependent large-scale fields (e.g. wind, temperature, water vapour, surface pressure, and sea-surface temperature (SST) at model sea grid-boxes) at their boundaries; this information is provided by a version of the Hadley Centre GCM, HadCM3 (Gordon et al. 2000; Collins et al. 2001). HadCM3 was one of the major models used in the IPCC Third and Fourth Assessments and also contributes to the Fifth Assessment. It is a coupled climate model that has been used extensively for climate prediction and other climate sensitivity studies. The Providing Regional Climates for Impacts Studies (PRECIS), the third-generation Hadley Centre RCM is based on the atmospheric component of HadCM3 with substantial modifications to the model physics. Several studies have emphasized on regional climate modelling systems to quantify the uncertainty of the projected climate change at a regional scales with a coarse resolution (≈50 km) version of the PRECIS (Mohammad and Md 2012; Jones et al. 2012; Met Office Report 2012).

PRECIS simulation for Bangladesh shows a good performance while calibrating temperature and rainfall for the region. It was found to produce successful seasonal forecasting of meteorological parameters like rainfall and temperature for Bangladesh (CCC 2009; Nazrul Islam 2009; Mohammad et al. 2012). State level adaptation studies in India also have been done for Madhya Pradesh and Odisha using model outputs from PRECIS generated by IITM, Pune (Synthesis Report 2012; Final Report 2012). Rupakumar simulated the regional climate of India by using PRECIS model for the baseline (1961–1990) as well as for the end of the century (2071–2100) for A2 and B2 SRES scenarios (Rupa Kumar et al. 2006). Krishnakumar used PRECIS to simulate the regional climatology of India for SRES scenario A1B (Krishna Kumar et al. 2011). Several PRECIS-based RCM applications on subregional scales were carried out by various studies in India (Bhaskaran et al. 1996; Bhaskaran et al. 2012a; b; Kulkarni et al. 2013). The analyses from many CMIP3 GCMs over south Asia show that only six GCMs out of 18 are able to capture the precipitation pattern between models and observed precipitation with a relatively small root mean square difference compared to observations over India; however, HadCM3 was identified as a suitable global model which simulates the Indian summer monsoon with its interannual variability better than the other CMIP3 models (Annamalai et al. 2007; Jones et al. 2004). Therefore, it was used to force the PRECIS simulations presented in this study. PRECIS is found to be an adequate tool for dynamical downscaling of climate features to generate detailed information for the Tamil Nadu region. Furthermore, limited regional climate change studies have been carried out for Tamil Nadu using RCMs with multiple ensemble members with a resolution of 25 km to assess climate change and its uncertainty. There is particularly an emerging need to produce high-resolution climate change information with its uncertainty range for a few key climate variables for Tamil Nadu state to enable adaptation options for the water, agriculture, and manufacturing sectors. This is the first ever study for this region that utilizes six-member transient regional climate model simulations at 25 km horizontal resolution to project changes in key climate parameters and the associated uncertainty. Climate variability and climate change projections for the climate parameters maximum temperature (max. temp.), minimum temperature (min. temp.), and rainfall at both the long-term annual and seasonal scales over the entire Tamil Nadu with agro-climatic zone (ACZ) wise distributions is attempted in this paper.

1.1 Current climatology over Tamil Nadu

The climate of Tamil Nadu is mainly of tropical semiarid type. The geographical location of Tamil Nadu makes it as one of the most vulnerable maritime states in India particularly to tropical cyclones and their associated storm surges. It is frequently subjected to extreme weather conditions of flooding in coastal districts and severe droughts chronically in some areas and periodically in others. The temperature in summer seldom rises above 45 °C and in winter seldom falls below 18 °C. Temperatures and humidity remain relatively high all year round. Tamil Nadu gets rainfall from the northeast (NE) and southwest (SW) monsoon seasons. As per the SoE report (2005) of Tamil Nadu, the normal rainfall in the state is about 950 mm with an average number of 50 rainy days. Being located on the leeward side of the Western Ghats, it gets only about 32 % of the annual rainfall during the SW monsoon season (June–September). During the NE monsoon, the principal rainy season (October–December), it receives about 48 % of the annual total rainfall (Balachandran et al. 2006; Selvaraj and Rajalakshmi 2011; Indira and Stephen Rajkumar Inbanathan 2013). The rainfall in this season is highly variable due to its cyclonic nature. Tamil Nadu is divided into seven agro-climatic zones: northeastern, northwestern, Cauvery delta, western, high-altitude, southern and high rainfall zones. The total area covering each zone with districtwise distribution is given in Table 1. Rainfall over the coastal areas is higher and decreases towards inland as the rainfall-causing systems are forming over the Bay of Bengal and moving westwards towards the coast of Tamil Nadu. The windward (eastern) side of the Eastern Ghats is having more rainfall than the leeward (western) side. The total amount of rainfall in the season is not constant and have inter seasonal and intra seasonal variability due to formation/non-formation of rain-bearing systems and their spatial variations.

Table 1 Seven agro-climatic zones of Tamil Nadu with districtwise distributions

Agro-climatic zone	Total area (sq. km)/vulnerable area (%)	District name
Northeastern	31,194/5.4	Tiruvallur, Chennai, Kancheepuram, Vellore, Thiruvanamalai, Villupuram, Cuddalore
Northwestern	18,271//48	Dharmapuri, Krishnagiri, Salem, Namakkal
Western	15,678/77	Erode, Coimbatore, Karur, Dindigul, Tirupur
Southern	36,655/7	Pudukotai, Theni, Sivaganga, Virudhnagar, Ramanathpuram, Thoothukudi, Tirunelvelli, Madurai
Cauvery delta	24,943/2	Perambalur, Trichy, Ariyalur, Nagapattinam, Thanjavur, Thiruvarur
High rainfall	1684/0	Kanyakumari
High altitude	2549/45	Nilgiris, Coimbatore

Area which is more exposed and sensitive to maximum temperature rise is defined as highly vulnerable area (%), predicted by the models (PRECIS) with respect to maximum temperature change by the end of the century

2 Methodology

2.1 Experiments and ensemble selections

PRECIS is an atmospheric and land surface model of high resolution (up to 25 km) and limited area model which can run with boundary data from a global climate model. A more complete description of PRECIS is provided by Jones et al. (2004). HadCM3Q is used in this study to force the PRECIS simulations over a large domain which covers India and neighbouring countries. The Met Office Hadley Centre is now able to provide boundary data from a 17-member perturbed physics ensemble (HadCM3Q0-Q16, known as 'QUMP') for use to drive PRECIS in order to allow users to generate an ensemble of high-resolution regional climate simulations. The detailed descriptions of the QUMP ensembles members are discussed by Murphy et al. (2009). Exploring the range or spread of projections from different GCMs enables us to gain a better understanding of the uncertainties in climate change scenarios that arise from differences in model

Table 2 Model ranks based on their RMSE in reproducing summer monsoon rainfall over the wider Indian region

Rank	Model	RMSE (mm/day)	Mean (baseline)			Standard deviation (baseline)	
			Mean temp. (°C)	Max. temp (°C)–Min. temp. (°C)	Rainfall (mm/day)	Mean temp. (°C)	Rainfall (mm/day)
1	*HadCM3Q5*	0. 696347	27.6 /	(33.7–23.0)	1.3	0.7	0.47
2	*HadCM3Q0*	0.724145	27.2/	(32.8–22.4)	1.9	0.5	0.31
3	*HadCM3Q1*	0.767074	27.7/	(34.0–22.6)	1.0	0.5	0.40
4	HadCM3Q2	0.787332		–	–	–	–
5	*HadCM3Q13*	0.828461	27.8/	(33.4–23.5)	2.4	0.4	0.45
6	HadCM3Q10	0.830466		–	–	–	–
7	HadCM3Q9	0.873998		–	–	–	–
8	HadCM3Q3	0.886497		–	–	–	–
9	HadCM3Q12	0.895064		–	–	–	–
10	HadCM3Q8	0.897465		–	–	–	–
11	HadCM3Q16	0.915826		–	–	–	–
12	*HadCM3Q7*	0.919369	27.6 /	(33.4–23.2)	1.5	0.4	0.38
13	HadCM3Q4	0.924763		–	–	–	–
14	*HadCM3Q11*	0.967986	27.9/	(33.7–23.6)	1.6	0.4	0.33
15	HadCM3Q6	1.00132		–	–	–	–
16	HadCM3Q14	1.08408		–	–	–	–
17	HadCM3Q15	1.28319		–	–	–	–
*	IMD observed (1970–2000)		27.1/	(33.0–22.8)	2.9	0.3	0.40

The models with italic highlights represent the selected models for this present study. Simulated data from the six models are evaluated with IMD observed data for the baseline period (1970–2000) formulation. In order to provide a range of plausible climate outcomes while minimizing the resource requirement, a subset of six ensemble members from the 17-member QUMP ensemble is selected to downscale from the global scale to obtain region-specific information. The selection of the subset of six members from the 17 available QUMP members for India is done by examining simulations from each of the GCMs against observations. Specifically, the behaviour of the Indian summer monsoon is considered as the major driver of the timing, magnitude, and variability of wet-season rainfall and its extremes to access the impact on the water resources. Here, our focus is to look for models that demonstrate reasonable skills in simulating rainfall patterns over the study region as well as the wider Indian subcontinent. We assessed precipitation bias for the period 1970–2000. Based on the root mean square errors (RMSE) calculated for the entire region, the models are ranked as given in Table 2. The RMSE values are assigned in millimetres per day to all the models according to their global performance in rainfall simulations. The magnitudes of the biases are also similar except perhaps for the model versions HadCM3Q0, which show a relatively smaller bias. Most of the models show reduction in future rainfall over southern India. Nine models show an east-west gradient over the sea in rainfall change projections (HadCM3Q0, HadCM3Q1, HadCM3Q5, HadCM3Q6, HadCM3Q9, HadCM3Q12, HadCM3Q13, HadCM3Q14 and HadCM3Q16). We desired to pick four out of these nine model versions that have smaller RMSE. Although the model versions HadCM3Q11 and HadCM3Q7 show strong north-south precipitation gradient (ranked 14 and 12, respectively), we proposed to pick these two members for the variety. Based on the model performance and variety of changes in precipitation patterns, the best six ensemble members, viz. HadCM3Q0, HadCM3Q1, HadCM3Q5, HadCM3Q7, HadCM3Q11 and HadCM3Q13 are taken in order to show the large uncertainties still existing in future climate change projections. Coincidentally these six members also have varying levels of reduction in rainfall in the future, with HadCM3Q0 showing a slight increase. Based on a preliminary evaluation of these 17 global runs for their ability to simulate the gross features of the Indian monsoon, the lateral boundary conditions (LBCs) of six QUMP simulations are provided by the Hadley Centre, UK. These boundary data have been derived from ERA40 [European Centre for Medium-Range Weather Forecasting (ECMWF)] (Simmons et al. 2007). This reanalysis dataset was produced with an improved GCM compared to that used in the construction of ERA15. The reason for utilizing ERA40 reanalysis data sets which represent well the key characteristics of the monsoon circulation are discussed by Uppala and Coauthors 2005 and

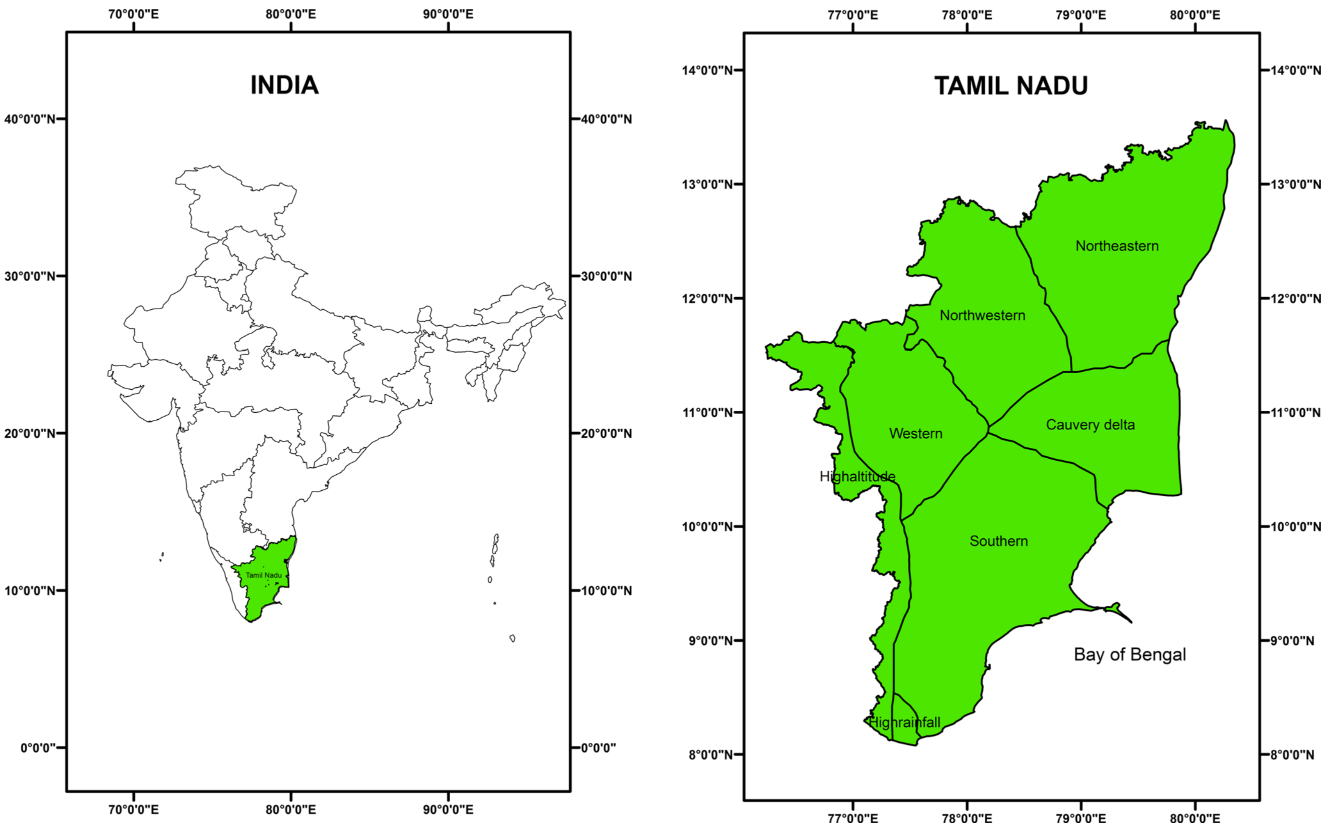


Fig. 1 Study area: seven agro-climatic zones of Tamil Nadu

McSweeney et al. 2012. HadCM3Q uses flux adjustments to ensure that the SSTs remain close to climatological values during a control period, while allowing SSTs to vary from natural variability and from atmospheric forcings such as CO_2 (Simon et al. 2004). Similarly, each of the models has its own unique pattern of flux adjustments. The external forcing is from SRES A1B emission scenario. Our objective is to achieve a variety of future projections, and our focus is to look for models that demonstrate reasonable skills in simulating rainfall patterns during summer monsoon over Tamil Nadu as well as over the wider Indian subcontinent. The simulations follow the protocol set by IPCC Fourth Assessment Report (AR4) at 25 km×25 km horizontal resolution over the whole India which includes Tamil Nadu with a transient runs of 130 years. The calibration and validation is considered for Tamil Nadu which has boundaries at 08° 05′ N to 13° 35′ N and 76° 15′ E to 80° 20′ E as depicted in Fig. 1. We have used GIS technology in this study to better understand the geographical problems at a regional scale. All the maps have been developed by using ArcGIS tool with spatial interpolation methods, and the trend analyses have been performed using Mann-Kendall trend test at 0.05 significance level for both max. temp. and min. temp. and 0.1 significance level for rainfall. By Mann-Kendall test, we want to test the null hypothesis, H0, of no significant trend and against the alternative hypothesis, H1, where there is an increasing or decreasing monotonic trend. The detailed procedures and methods on Mann-Kendall test are discussed by Gilbert (1987).

2.2 Observed climate variability of Tamil Nadu with model evaluation

We gathered observed mean, maximum and minimum temperatures and rainfall data for the recent 30 years (1970–2000) from India Meteorological Department (IMD) for Tamil Nadu. We interpolated precipitation data at 0.5°×0.5° grid to assess the model simulations over Tamil Nadu at 0.25°×0.25° for the period 1970–2000 (Rajeevan et al. 2008). The station temperatures are interpolated at 1°×1° grid for this model validation exercise (Srivastava et al. 2008). PRECIS-simulated mean temperature and annual rainfall is calibrated with the IMD observed data during the baseline period to understand the efficacy and performance of the models. Since the IMD gridded data is of 0.5°x0.5° resolution, the grid value of the model data is compared with the observed data representing that grid. The model outputs are compared with those of the observed values for mean max. temp., mean min. temp. and annual rainfall. As we know from the limitations of the models with respect to accuracy that the models cannot simulate any meteorological parameters with 100 % accuracy; this is due to the short length of the observations and the large spatial variability in precipitation, particularly in mountainous regions, where rain gauge networks are not often dense enough (High 2010; Nazrul Islam 2009).

The climate change assessments have been done for both temperatures and precipitation by comparing model generated baseline data for the present-day climate with model generated future data.

Mathematically, it can be represented as,

$$(\mathrm{Model}_{\mathrm{future}} + \mathrm{bias}) - (\mathrm{Model}_{\mathrm{baseline}} + \mathrm{bias}) = \mathrm{Change}$$

A common assumption is made based on the stationarity of the model bias. This implies that the empirical relationships in the correction algorithm and its parameterization for the current climate conditions do not change over time and are also valid for future climate conditions (Maraun 2012; Ehret et al. 2012; Teutschbein and Seibert 2013). Therefore, the future climate change assessments in this study are performed by ignoring the model biases. Future projections are made with respect to the model-generated baseline data instead of actual observed data obtained from IMD. Actual observed data are being used only for model evaluation/validation purpose, i.e. for comparing with the model baseline data for the present-day climate simulation periods (1970–2000) to ensure that the model generates some realistic values with respect to the observed climatology over Tamil Nadu region. So the performance of future temperature change is calculated by taking

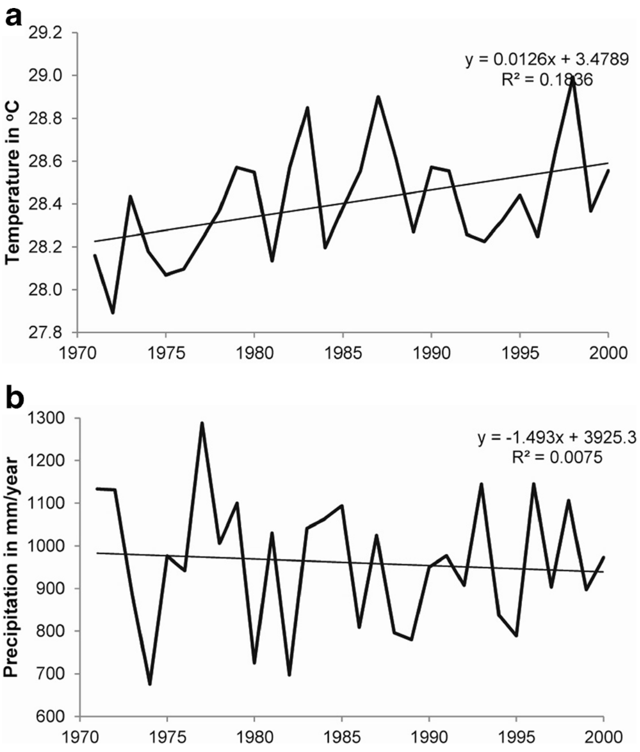
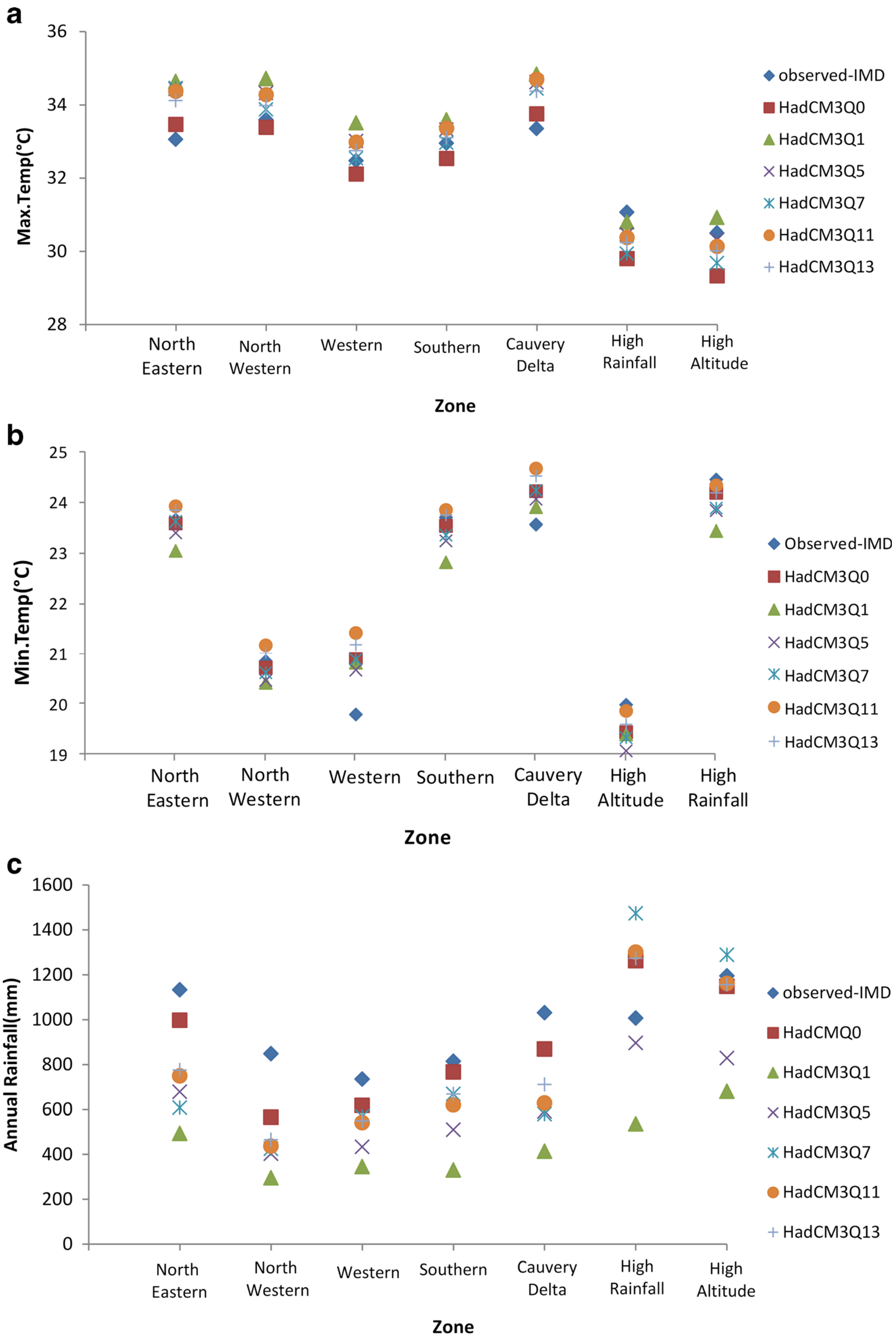


Fig. 2 **a** Observed annual mean temperature trend for Tamil Nadu from 1970 to 2000. **b** Observed annual mean rainfall trend for Tamil Nadu from 1970 to 2000

Fig. 3 Evaluation of GCMs with IMD observations data for the averaged **a** annual mean max. temp. (°C), **b** annual mean min. temp. and **c** annual rainfall for the period 1970–2000 (agro-climatic zone wise)



the difference of model-generated future and baseline values. To remove the influences of dispersion, the standardized temperature anomaly is calculated by subtracting the mean from each observation then dividing by the standard deviation. Similarly, the performance of rainfall change is calculated by taking the difference of future and observed values divided by observed values from the model in percentage.

3 Results and discussions

An analysis of the IMD observed data for the temperature and precipitation patterns over 30 years period from 1970 to 2000 indicates slight increase and decrease trends, respectively, as shown in Fig. 2a, b. On applying the Mann-Kendall trend test on observed IMD temperature data, it is seen that the

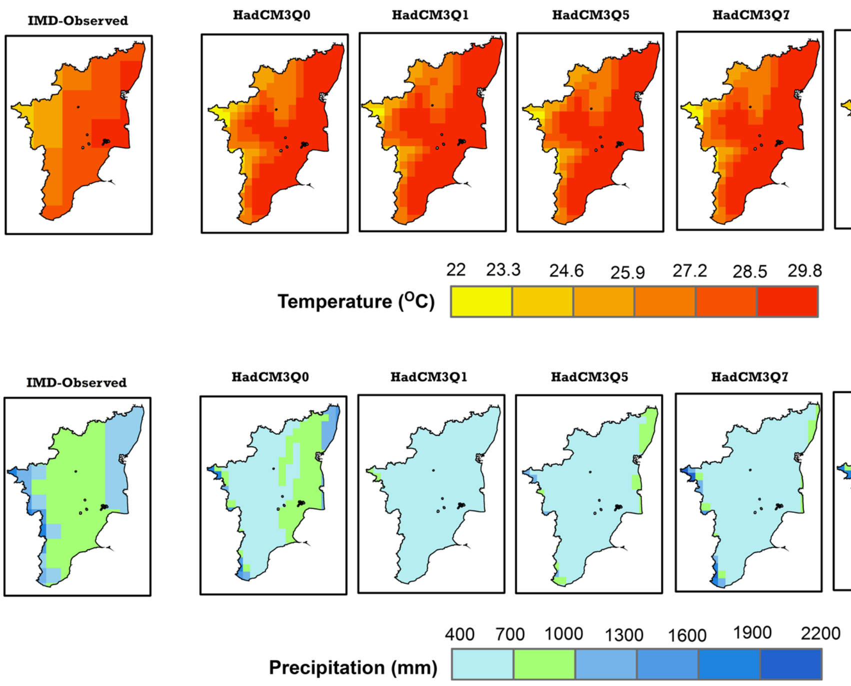


Fig. 4 Model evaluation: GCMs spread (annual mean temperature and annual rainfall) over Tamil Nadu with IMD observation during the period 1970–2000

increased trend is significant at 0.05 level as the *p* value (0.013) is less than the significance level α (alpha)=0.05. The observed trend for precipitation is not significant since *p* value (0.809) is greater than the significance level α (alpha)= 0.1. PRECIS simulation for Tamil Nadu shows a reasonable skill in simulating temperature and rainfall patterns for the region, though there are areas where the model underestimates rainfall values. It is very much successful for annual as well as seasonal projections of meteorological parameters like rainfall and temperature in various temporal and spatial scales, but significant exceptions are observed at some regions where the model is underestimating the actual IMD data. In general, the magnitudes and frequency characteristics of the variability of the surface temperature and precipitation of different ensemble members of PRECIS on annual time scales are in good agreement with the observations. Figure 3a, b, c show the model comparisons with the IMD observed values during the period 1970–2000 for max. temp, min. temp. and annual rainfall, respectively, for Tamil Nadu with ACZ-wise distributions. A simulated spatial pattern of mean surface temperature and rainfall variability for all the models over Tamil Nadu is qualitatively similar to that observed, although there are some underestimations and regional errors found in case of the annual rainfall variability (Fig. 4). However, from Table 2 (mean and standard deviation), it is observed that PRECIS performance is quite reasonable, realistic, and statistically significant while assessing with IMD observed data set. The RCM shows good skill while simulating the past climate of Tamil Nadu where an average precipitation of 2.9 mm/day is observed for the whole state. Similarly, simulated average annual mean temperature, max. temp. and min. temp. are also with well agreement with the IMD which shows 27.1, 33.0 and 22.8 °C, respectively (Table 2).

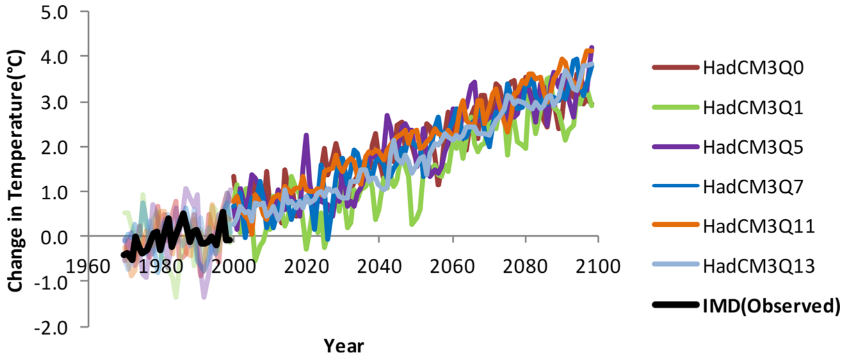


Fig. 5 Temperature anomaly over Tamil Nadu for the period 1970–2100 with respect to the present-day climate

Table 3 Results of the Mann-Kendall trend test for mean temperature data from all the six models for the whole Tamil Nadu

Model	Mann-Kendall statistic (S)			Kendall's tau			*p* value (two-tailed test)			Alpha	Test interpretation		
	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s		2020s	2050s	2080s
HadCM3Q0	227	173	−42	0.488	0.398	−0.111	<0.0001	0.002	0.422	0.05	R-H0	R-H0	A-H0
HadCM3Q1	77	251	108	0.166	0.577	0.286	0.199	<0.0001	0.034	0.05	A-H0	R-H0	R-H0
HadCM3Q5	147	119	152	0.316	0.274	0.402	0.012	0.035	0.002	0.05	R-H0	R-H0	R-H0
HadCM3Q7	263	243	182	0.566	0.559	0.481	<0.0001	<0.0001	0.000	0.05	R-H0	R-H0	R-H0
HadCM3Q11	315	265	190	0.677	0.609	0.503	<0.0001	<0.0001	0.000	0.05	R-H0	R-H0	R-H0
HadCM3Q13	313	287	242	0.673	0.660	0.640	<0.0001	<0.0001	<0.0001	0.05	R-H0	R-H0	R-H0

R-H0 rejected null hypothesis, *A-H0* accepted null hypothesis

3.1 Temperature projections

The future warming over Tamil Nadu is widespread, and the magnitude differs spatially. Figure 5 shows the mean air temperature standardized anomaly over Tamil Nadu for the period 1970–2100 based on IMD gridded data. It gives a linear trend of 3.1 °C change for the future 100 years with reference to the baseline. The temperature intensifies more by the end of the century in the range of 2.8 to 3.7 °C. On running the Mann-Kendall trend test on temperature data during the projection periods 2020s, 2050s and 2080s from the six models, it is observed that the increased trend is highly significant at 0.05 level as the p value is less than the significance level α (alpha)=0.05, H0 is rejected (Table 3).

3.1.1 Max. temp. projections

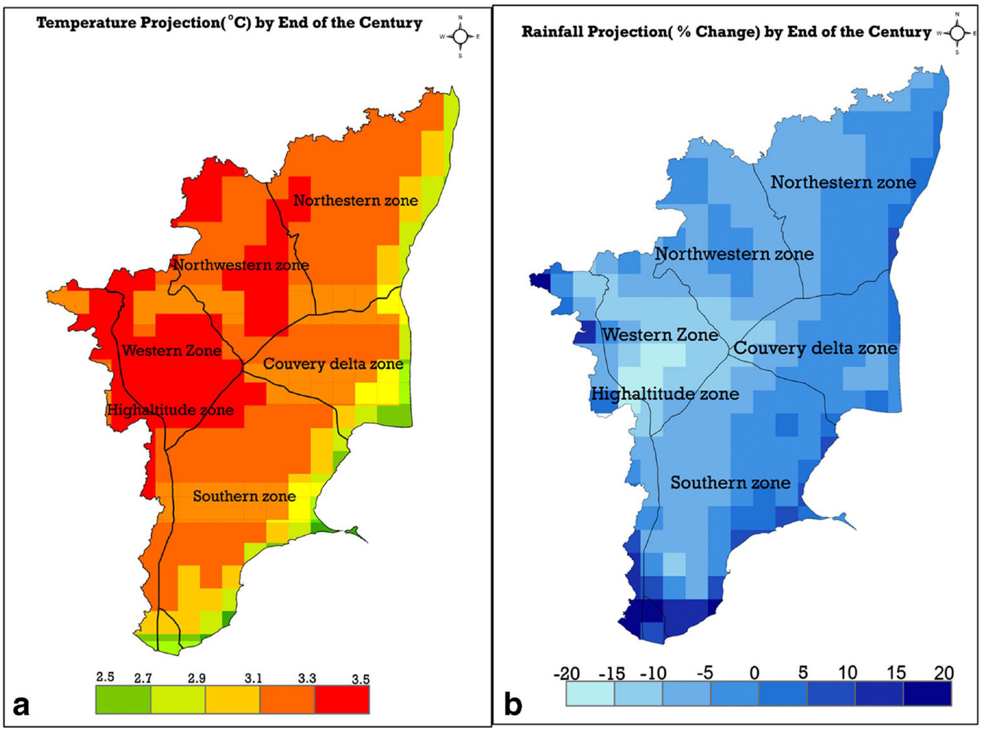
Projections of annual mean max. temp. over Tamil Nadu as a whole for 2020s, 2050s and 2080s with reference to the baseline period indicate an average increase of 0.8–1.3, 1.9–2.4 and 2.9–3.5 °C respectively at the emission rate of A1B (Table 4). Analyses of the ACZ-wise projections generally indicate a slight increasing tendency from coastal area to the interior. Projections for the century indicate a minimum increase of 2.5–3.2 °C over high rainfall zone and 2.6–3.5 °C for rest of the zones. A maximum increase of 3.5 °C is projected over western zone which shows 77 % of the total area is more exposed and sensitive to warming in compared to other zones (Fig. 6a and Table 1). Due to the rapid growth in urban agglomeration and industrialization, western zone including the major districts Coimbatore, Tirupur, Erode and Karur may experience the maximum rise in temperature resulting in a dry weather in the future. The vulnerability measures have been defined in terms of area (in percentage) of Tamil Nadu state (ACZ-wise) which are more exposed and sensitive to elevated temperatures resulting in harsh summers with an oppressive heat in the future due to the maximum rise in temperature. Further, during March–May (MAM), all the models projected an average increase in temperature above 40 °C when compared to the baseline which shows above 37 °C for Tamil Nadu as a whole (Fig. 7).

Table 4 Model simulated average annual temperature (max. temp. and min. temp.) and rainfall change projections: ACZ-wise projections

Agro-climatic zone	Projections for 2020s, 2050s and 2080s with reference to baseline (1970–2000)								
	Max. temp (°C)			Min.temp (°C)			Annual rainfall (%)		
	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
Northeastern	0.7–1.4	2.1–2.5	2.6–3.5	1.0–1.4	2.3–2.7	3.2–3.9	−1 to −4	−3 to −12	−2 to −11
Northwestern	0.9–1.4	2.1–2.7	2.6–3.5	0.8–1.7	2.5–2.9	3.0–4.2	−1 to −8	−1 to −10	−1 to −10
Western	1.0–1.4	2.0–2.7	2.6–3.5	0.8–1.5	2.4–2.8	2.8–3.9	−2 to −9	−2 to −8	−5 to −20
Southern	0.9–1.3	1.9–2.4	2.6–3.4	0.7–1.4	2.2–2.6	3.2–3.7	−1 to −4	2 to 6	7 to 8
Cauvery delta	0.8–1.3	2.1–2.4	2.6–3.4	0.7–1.5	2.3–2.7	3.3–3.8	−1 to −6	−2 to −13	−1 to −9
High rainfall	0.5–1.0	1.9–2.3	2.5–3.2	0.6–1.3	1.3–1.8	2.2–2.9	2 to 12	8 to 14	10 to 20
High altitude	1.0–1.4	2.2–2.6	2.8–3.5	0.7–1.4	1.4–2.6	2.6–3.7	1 to 6	4 to 13	5 to 20
Tamil Nadu	0.8–1.3	1.9–2.4	2.9–3.5	0.7–1.4	1.5–2.7	2.7–3.8	−2 to −7	−1 to −4	−4 to −9

In the rainfall projection, "−ve" shows a decrease (% change) and "+ve" shows an increase (% change)

Fig. 6 Average change in **a** annual mean max. temp (°C) and **b** annual rainfall projections by the end of the century in a spatial scale (agro-climatic zone-wise)



3.1.2 *Min. temp. projections*

Projections of annual mean min. temp. over Tamil Nadu as a whole for 2020s, 2050s and 2080s with reference to baseline indicates an average change of 0.7–1.4, 1.5–2.7 and 2.7–3.8 °C, respectively. By the end of the century, a general maximum increase of 3.0–4.2 and 2.8–3.9 °C is projected over the northwestern and western part of Tamil Nadu including the districts Nilgiris, Dharmapuri, Salem, Namakkal, Krishnagiri, Dindigul, Coimbatore, Tiruppur, Karur and Erode, while some of the eastern parts of the coastal districts like Chennai, Nagapattinam, Ramanathapuram and Kanyakumari show minimum increase (Table 4). ACZ-wise distributions indicate maximum increase in interior parts of Tamil Nadu consisting of northwestern, Cauvery delta and western zone.

3.2 Rainfall projections

For a future warmer climate, the current generation models (IPCC AR5 models) indicate that globally averaged precipitation generally increases in the areas of regional tropical precipitation maxima (such as the monsoon regimes) and in high-altitude regions (Meehl et al. 2007). Some of the CMIP3 multi-model ensembles for the A1B scenario project no change in monsoon precipitation over most of India (Solomon et al. 2007), and also by the end of the century, the Indian monsoon dynamical circulation is likely to be weakened under the A1B scenario (Ueda et al. 2006). Further, a GCM projection studied by Kumar et al. (2013) shows that a weak reduction of monsoon rainfall approximately ~5 % is projected over parts of peninsular India, and by the end of the 21st century;

Fig. 7 Monthly mean max. temp. (*lines*) and monthly rainfall projections (*bar*) for whole Tamil Nadu during 2020s (*red*), 2050s (*green*) and 2080s (*violet*) with respect to baseline (*blue*)

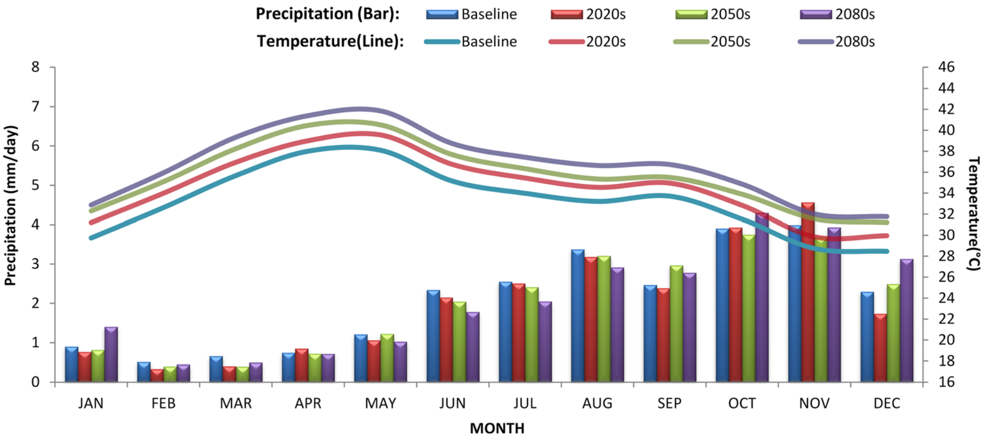


Table 5 Results of the Mann-Kendall trend test for rainfall data from all the six models for the whole Tamil Nadu at 0.1 significance level

Model	Mann-Kendall statistic (S)			Kendall's tau			*p* value (two-tailed test)			Alpha	Test interpretation		
	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s		2020s	2050s	2080s
HadCM3Q0	15	47	104	0.032	0.108	0.275	0.814	0.416	0.041	0.1	A-H0	A-H0	R-H0
HadCM3Q1	103	13	−76	0.222	0.030	−0.201	0.083	0.832	0.140	0.1	R-H0	A-H0	A-H0
HadCM3Q5	27	27	42	0.058	0.062	0.111	0.661	0.646	0.422	0.1	A-H0	A-H0	A-H0
HadCM3Q7	−83	95	28	−0.178	0.218	0.074	0.165	0.094	0.597	0.1	A-H0	R-H0	A-H0
HadCM3Q11	3	19	−64	0.006	0.044	−0.169	0.973	0.750	0.216	0.1	A-H0	A-H0	A-H0
HadCM3Q13	79	51	−8	0.170	0.117	−0.021	0.187	0.376	0.891	0.1	A-H0	A-H0	A-H0

R-H0 rejected null hypothesis, *A-H0* accepted null hypothesis

the decreasing precipitation over the east coast of peninsular India could intensify more. A study from Krishna Kumar shows that the projection by the end of the century indicates a slight decrease in monsoon rainfall over Tamil Nadu (Krishna Kumar et al. 2011). Further, several studies on Indian monsoons have clearly pointed out that the monsoon rainfall is trendless and randomly fluctuates over a long period of time Guhathakurta and Rajeevan (2008). Based on the present study, the annual rainfall projections from each individual ensemble members for the periods 2020s, 2050s and 2080s indicate a general decrease in rainfall being about 2–7, 1–4 and 4–9 % respectively with reference to the baseline for Tamil Nadu as a whole. However, significant exceptions are noticed over some pockets of high-altitude zone and high rainfall zone areas where an increase in rainfall ranging between 1–12, 4–14 and 5–20 % for the next three projections from the baseline is seen (Table 4 and Fig. 6b). A slight average decrease during the SW monsoon (June–September) and an average increase during the NE monsoon (October–December) are projected for the periods 2020s, 2050s and 2080s respectively with reference to baseline periods, but the intensity of monsoon average rainfall is projected to increase (Fig. 7). The results from Mann-Kendall trend test at 90 % confidence level show no significant trend in future projections of annual rainfall over Tamil Nadu as the *p* value is greater than the significance level α (alpha)=0.01 (Table 5). For high rainfall and high-altitude zones, annual rainfall projections indicate an increasing trend whereas for the rest of the zones, no trend has been seen for the future 100 years (Fig. 8). Further, analyses of daily extremes of rainfall show that during the SW monsoon season (JJAS), the number of days with precipitation above 5 mm/day indicates a decrease of 3 % by the end of the century i.e. in the baseline, the number of days shows 3249, but in the future, it is as high as 3376 (127 days more when compared to baseline). Similarly, during the NE monsoon period (OND), the number of days of rainfall above 25 mm/day indicates an increase of 1 % (i.e. 17 days in baseline and 27 days in future period) over the whole Tamil Nadu as shown in Fig. 9; however, the rising trends in the frequency and the magnitude of extreme rainfall events are not significant.

3.3 Model performances

In this paper, we have used the perturbed physics ensemble (PPE) approach which is used to perturb physical parameters and produce a range of future climates based only on one climate model. Perturbed members HadCM3Q1-HadCM3Q16 are numbered according to the value of their global climate sensitivity; thus, HadCM3Q1 has the lowest

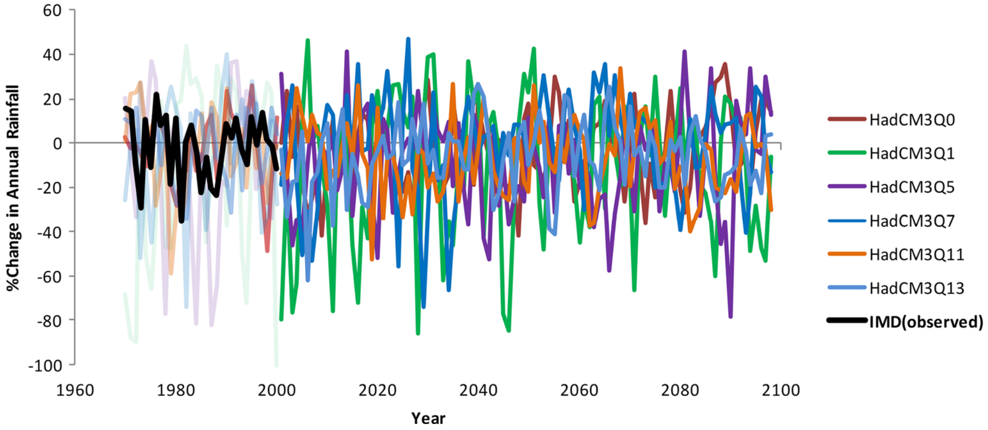


Fig. 8 Rainfall anomaly (% change) over Tamil Nadu for the period 1970–2100 with respect to the present-day climate

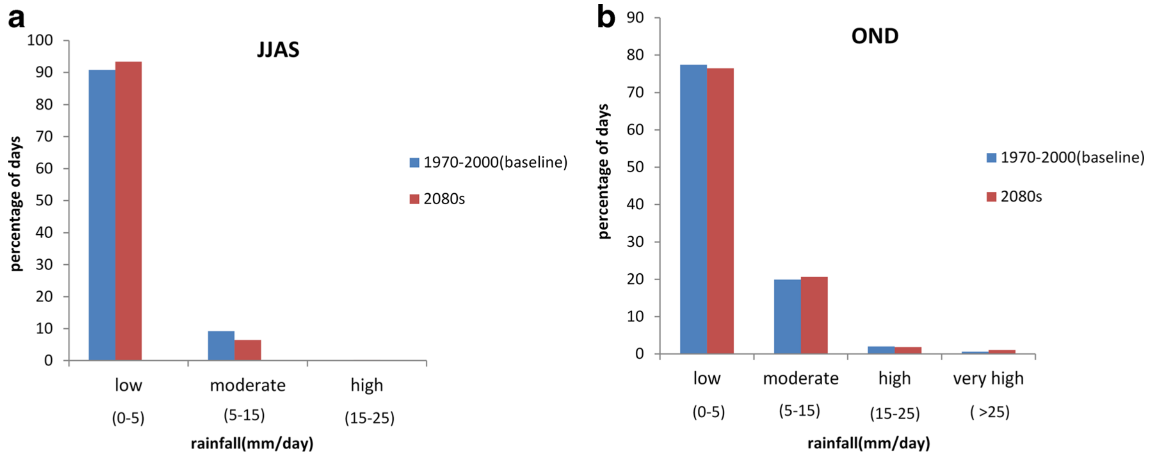


Fig. 9 Frequency distribution (% of days) for the daily rainfall events over Tamil Nadu during **a** JJAS (June–September) and **b** OND (October–December)

global average temperature response to a given increase in atmospheric CO_2, and HadCM3Q16 has the highest (Jones et al. 2012). Six members of the QUMP ensemble are selected in order to produce the possible range of variations in the future projections. We have selected a member subject to the requirement that it captures the annual variations with full range of outcomes produced by the QUMP ensemble, while any member that does not represent the Indian climate realistically are excluded from the experiment. Though the simulations of all the six models for the present day climates show more variations, the mean values show similar for all the models. HadCM3Q1 shows an east-west gradient over the sea in rainfall change projections. We desired to pick this model version since it is able to capture the precipitation pattern between model and observed precipitation with a relatively smaller RMSE difference compared to observation over India, but for Tamil Nadu region, the model performance is poor with respect to rainfall projection. This ensemble shows quite reasonable and realistic performance over India as a whole when compared to Tamil Nadu state but to quantify the uncertainty range, we have selected this ensemble. We did not find any good reason to eliminate this ensemble on the grounds on validation during the present-day climate simulations. Though the model shows poor performance during the current climate simulation periods, we cannot guarantee that the model will also show poor performance in the future precipitation projections. Results from many forerunner papers show that simulations of PRECIS have been made at 50 km×50 km horizontal resolution with limited ensemble members for generating high-resolution climate change scenarios over the Indian region (Rupa Kumar et al. 2006; Krishna et al. 2010; Krishna Kumar et al. 2011; Kulkarni et al. 2013); however, not many studies are available over the Tamil Nadu regions that study the climate change scenarios using simulations from high-resolution models, but we have simulated the models at 25 km×25 km horizontal resolution with six ensemble members suitable for this region. However, the uncertainty still exists in our approach while providing the possible range of variations. We expect that performances of all the 17-member ensemble 'runs' to test for variations and sensitivity to different scenarios of future green house gas emissions may provide a better understanding of how the difference in model formulation can lead to uncertainty in the projections.

4 Conclusion

PRECIS-generated rainfall and temperature scenarios are evaluated with ground-based observed data during 1970–2000 in Tamil Nadu. In this work, rainfall and temperature projection for Tamil Nadu is performed experimentally for 2020s, 2050s and 2080s. Model simulation using PRECIS shows more realistic results and performs well by representing the present climatology of Tamil Nadu. For the whole state, projections by end of the century indicate warmer summers, maximum temperature increasing by about 3.1 °C with a general maximum increase of 3.3–3.5 °C over western zone and minimum temperature by about 3.5 °C. The min. temp. projections consistently show higher values when compared to max. temp. with a difference ranging from 0.2 to 0.5 °C for different projections. No significant change in the rainfall is seen from the baseline by the end of the century for the whole Tamil Nadu. However, there is a slight increase in rainfall during the northeast monsoon season (October–December). Such climate change information can be utilized by various policymakers and stakeholders to design suitable planning and formulating adaptation strategies for different sectors such as agriculture, water resources, forest and biodiversity, coastal area management, health and habitat, etc.

The future projections clearly indicate an increased probability of extreme temperature spells that would be expected to be very detrimental for public health. In this aspect, government agencies from various sectors should pay attention to the expected impacts of future warming and decrease in rainfall over the Tamil Nadu state which may cause severe damage to the agriculture sector with respect to crop productions, water insecurities, species extinctions, etc. and pay the costs for this future climate damages.

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