

# Climate Change Projections over India by a Downscaling Approach Using PRECIS

Prasanta Kumar Bal<sup>1,2</sup>, Andimuthu Ramachandran<sup>1</sup>, Kandasamy Palanivelu<sup>1</sup>, Perumal Thirumurugan<sup>1</sup>, Rajadurai Geetha<sup>1</sup>, and Bhaski Bhaskaran<sup>3</sup>

<sup>1</sup>Centre for Climate Change and Adaptation Research, Anna University, Chennai, India

<sup>2</sup>National Centre for Medium Range Weather Forecasting, Ministry of Earth Science, Noida, India

<sup>3</sup>Fujitsu Laboratory of Europe, Middlesex, UK

(Manuscript received 16 September 2015; accepted 23 February 2016)

© The Korean Meteorological Society and Springer 2016

**Abstract:** This study presents a comprehensive assessment of the possible regional climate change over India by using Providing REgional Climates for Impacts Studies (PRECIS), a regional climate model (RCM) developed by Met Office Hadley Centre in the United Kingdom. The lateral boundary data for the simulations were taken from a sub-set of six members sampled from the Hadley Centre's 17-member Quantified Uncertainty in Model Projections (QUMP) perturbed physics ensemble. The model was run with 25 km × 25 km resolution from the global climate model (GCM) - HadCM3Q at the emission rate of special report on emission scenarios (SRES) A1B scenarios. Based on the model performance, six member ensembles running over a period of 1970-2100 in each experiment were utilized to predict possible range of variations in the future projections for the periods 2020s (2005-2035), 2050s (2035-2065) and 2080s (2065-2095) with respect to the baseline period (1975-2005). The analyses concentrated on maximum temperature, minimum temperature and rainfall over the region. For the whole India, the projections of maximum temperature from all the six models showed an increase within the range 2.5°C to 4.4°C by end of the century with respect to the present day climate simulations. The annual rainfall projections from all the six models indicated a general increase in rainfall being within the range 15-24%. Mann-Kendall trend test was run on time series data of temperatures and rainfall for the whole India and the results from some of the ensemble members indicated significant increasing trends. Such high resolution climate change information may be useful for the researchers to study the future impacts of climate change in terms of extreme events like floods and droughts and formulate various adaptation strategies for the society to cope with future climate change.

**Key words:** Climate change, GCM, RCM, PRECIS, Mann-Kendall trend test

## 1. Introduction

The study of climate change has been one the most important themes of empirical research since last two decades and more profoundly in the last decade. In this respect, Indian summer monsoon has shown predominant inter annual variabilities with extremes such as droughts and floods as

though a part of its natural variability. It has been observed in recent years that the frequency and intensity of heavy to very heavy rainfall events are increasing, whereas the events of low rainfall are declining in their frequency, particularly over the central parts of India (Goswami et al., 2006). Therefore, there is an urgent need of understanding the future trend and the implication towards climate change for the whole India but at a regional scale. The advances in the climate change modelling now enable best estimates and are likely to assess correct uncertainty ranges to be given for projected warming for different emission scenarios as per Intergovernmental Panel on Climate Change (IPCC, 2007). The only way to understand the impact of global warming on the Indian monsoon and to assess future monsoon climate is to use climate models based on the scenarios of emission of greenhouse gases (Rajeevan and Nanjundiah, 2009). Various climate models have been developed to study the Earth's climate system in the past and future at a global as well as regional scales, driven by assumptions based on different emission scenarios, which attempt to address the uncertainty in future emissions and might be an important aspect of assessing the future climate conditions. Using a range of different climate model simulations provides a better understanding of uncertainty in the projections (Jones et al., 2012) and by using ensemble approach (Jacob et al., 2007; Reichler and Kim, 2008), the uncertainty in the projections can be estimated quantitatively.

The simulation of several GCMs over the Indian monsoon region concludes that GCMs have difficulties in simulating the mean monsoon climate of Indian region (Sperber and Palmer, 1996; Giorgi and Mearns, 2002; Kang et al., 2002; Douville, 2005; Turner and Annamalai, 2012). The analysis of many GCMs (both atmospheric and atmosphere-ocean coupled models) showed that there are several problems in the representation of the mean Indian monsoon climate (Gadgil and Sajini, 1998; Kang et al., 2002; Wang et al., 2004b, 2005; Rajeevan and Nanjundiah, 2009). Furthermore, GCMs are often run at a very coarse resolution to depict the influence of complex topography on regional climate dynamics. As a result, "GCMs cannot access the spatial scales that are required for climate impact and adaptation studies" (WMO, 2002), whereas the high resolution RCMs are capable of producing more

Corresponding Author: Prasanta Kumar Bal, Centre for Climate Change and Adaptation Research, Anna University, Chennai 600025, India.

E-mail: prasantbal.cc@gmail.com

realistic precipitation climatologies (Kumar et al., 2013) and they can also produce appropriate projections to generate climate scenario at a regional scale. In the recent years, there has been an increase in the interest among different research groups in developing high resolution climate scenarios for India at a regional scale by using various high resolution RCMs. In this aspect, the simulation of the Indian summer monsoon circulation features and the associated rainfall by a numerical model had been the most challenging problems so far. Although some attempts have been made to simulate monsoon features and extreme weather events over India by RCMs. Kumar et al. (2013), in a series of simulations by using two RCMs (HadRM3 and REMO) forced by two GCMs (ECHAM5-MPIOM and HadCM3), observed that RCMs forced with GCMs are more efficient than GCM in simulating the inter-annual variability of the mean monsoon precipitation. The predictions of the temperature and precipitation by RCMs are quite close to the observations. Various attempts have been made to analyse the uncertainty of RCMs in simulating Indian summer monsoon (Bhaskaran et al., 1996, 2012; Dash et al., 2006). Earlier studies (Bhaskaran et al., 1996; May, 2004; Dash et al., 2006; Mukhopadhyay et al., 2010; Bhaskaran et al., 2012; Dimri et al., 2013) analysed the possible impacts of the global warming on Indian summer monsoon using the output of different RCMs and most of them reported that the model outputs concord well with the observations; and the high resolution RCMs are able to show improvement in the distribution of monsoon rainfall at spatial and temporal scales.

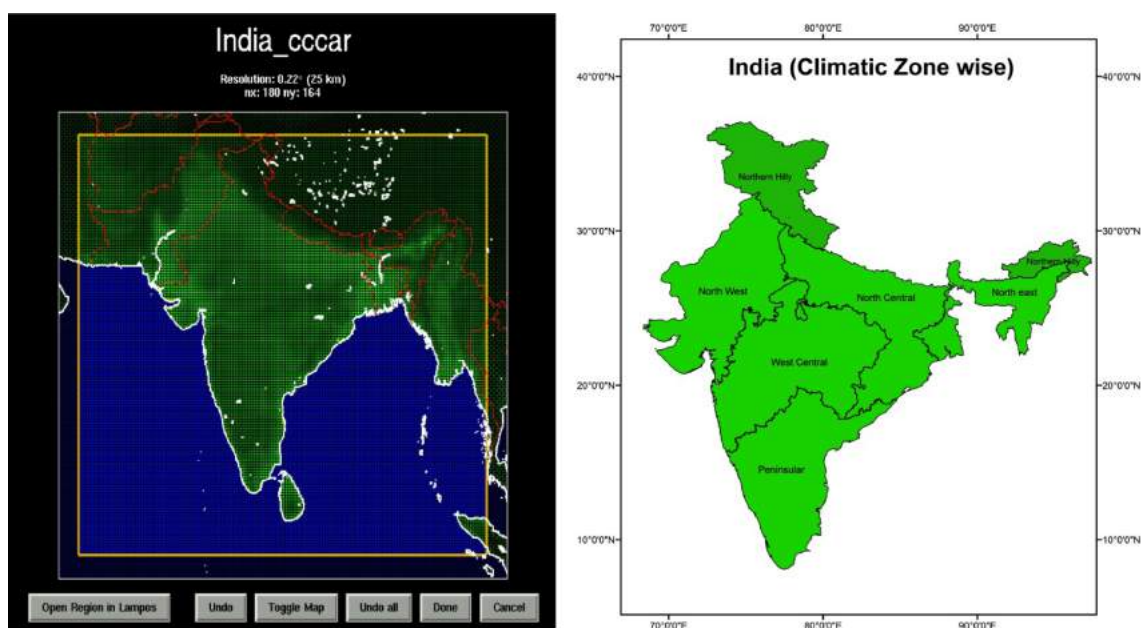
Furthermore, several studies emphasised on regional climate modelling systems to predict the future uncertainty of the climate variability and climate change at a regional scale over different regions of the globe with a coarse resolution using the Providing REgional Climates for Impacts Studies (PRECIS), that is the third generation Hadley Centre RCM (Zhang et al., 2006; Islam et al., 2007; Kotroni et al., 2008; Marengo et al., 2009; Nazrul Islam, 2009; Jones et al., 2012; Mohammad et al., 2012; Met Office Report, 2012), and the PRECIS simulations showed good performance when the temperature and rainfall for the analysed regions were calibrated. Hence, extensive debates still exist in understanding the possible characteristics of monsoon variability and its provenience in climate change. Many studies (Rupa Kumar et al., 2006; Krishna Kumar et al., 2010, 2011; Geethalakshmi et al., 2011; Revadekar et al., 2012; Kulkarni et al., 2013; Rajbhandari et al., 2014; Caesar et al., 2015) have used PRECIS to simulate high resolution climate change scenarios for the whole India at 50 km  $\times$  50 km horizontal resolution with limited ensemble members, and produced quite reasonable results for the prediction of meteorological parameters like rainfall and temperature over the region. These studies also provided a robust evaluation of the 17 HadCM3Q downscaled experiments over South Asia but most of these regional studies considered only single model projections and few had been in India that used RCM with multi ensemble and high resolution downscaling approaches to assess the future climate change uncertainties.

However, in this paper, the models are simulated at a 25 km  $\times$  25 km horizontal resolution with six ensemble members suitable for Indian region. The major advantage of using this 25-km regional model is its fidelity in representing the regional distribution of the present day monsoon rainfall. We present the results of RCM simulations using PRECIS for whole India with major climatic zones, for which there is an emerging need to understand the future trends of rainfall and temperature patterns, those will heavily impact agriculture, health, and the economy of the country. The main objective of this investigation was to project and assess regional climate changes over India in terms of surface temperature and precipitation under the SRES A1B scenario. It is expected that a better insight of these issues will be useful for the establishment of vulnerability and risk assessment methodologies and for the development of suitable adaptation strategies to reduce human risks. We have assessed 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 (south west and north east monsoons) over the whole India with climatic zone wise as well as state wise distributions.

The climatology over India has already been well documented (Hingane et al., 1985; Parthasarathy et al., 1994; Pant and Rupa Kumar, 1997). Herein we are addressing only some of the salient features of the observed climatology in terms of temperature and rainfall variabilities. As per the Climate Profile of India Report (2010), maximum temperatures rise sharply exceeding 45°C by the end of May and early June resulting in harsh summer in the north and north-west regions of the country including the states of Gujarat, North Maharashtra, Rajasthan and North Madhya Pradesh; and the Central Indian land mass becomes hot with daytime maximum temperatures reaching about 40°C at several locations. However, weather remains mild in coastal areas of the country. Further, the normal annual rainfall in the country is about 1182.8 mm. During the summer monsoon season (June-September: hereafter referred as JJAS), the country as a whole receives 70% to 90% of its annual rainfall (Pant and Rupa Kumar, 1997); whereas during the winter monsoon (October-December: shortly referred as OND), the south peninsular of India, particularly the east coast, receives a large amount of rainfall. Total annual rainfall over the whole Indian region during the JJAS showed a mean of 852 mm and a standard deviation of 84 mm based on the data during 1871-1990 (Krishna Kumar et al., 2011). The western coast and the north-eastern India is the wettest region which receive about 90% (approx. 3760 mm) of the annual average rainfall during June to October period. By contrast, the north-west of India which includes the desert of Rajasthan receives low annual average rainfall of 250 mm. Moreover, coastal parts of the south and north-east Indian states of Tamil Nadu, Andhra Pradesh, Orissa and West Bengal are severely affected by tropical cyclones (more details are available at <http://eprints.nottingham.ac.uk/2040/12/India.pdf>). The heaviest rains occur

**Table 1.** Six major climatic zones of India with state wise distributions.

Climatic Zone	Total Area (Sq.Km)	State Name
Peninsular	6,39,098	Andhra Pradesh, Karnataka, Tamil Nadu, Kerala, Goa
West Central	7,51,427	Madhya Pradesh, Maharashtra
North West	6,29,846	Punjab, Haryana, Rajasthan, Gujarat
North Central	5,71,020	Orissa, Bihar, Uttar Pradesh
North East	2,70,130	West Bengal, Sikkim, Assam, Nagaland, Meghalaya Manipur, Tripura, Mizoram
Northern Hilly	4,18,239	Jammu & Kashmir, Himachal Pradesh, Arunachal Pradesh
India	36,98,001	Six climatic zones including 25 major states

**Fig. 1.** Study Area: Schematization of domain selection over India using PRECIS.

over the hilly states in the north-east and along the mountainous west coast (the Western Ghats and the Konkan coast); significant rainfall occurs over the north eastern regions and foothills of the Himalayas. During winter, there is some rain over the northern parts and the southern peninsular India (associated with north-east monsoon) (Lal et al., 2001). Considering the temporal and spatial distributions of temperature and rainfall patterns, we classified the whole India into six major climatic zones: Peninsular, West Central, North West, North Central, North East, and Northern Hilly zones. The total area covering each zone with a state wise distribution is given in Table 1.

## 2. Model, data, and methodology

### a. Lateral Boundary Conditions (LBCs)

The PRECIS regional model has been used with horizontal resolutions of  $0.22^\circ \times 0.22^\circ$  or  $25 \times 25$  km at 19 different levels of the atmosphere, the lowest at  $\sim 50$  m and the highest at 0.5 hPa (Cullen, 1993) from the surface to 30 km in the stratosphere

and four levels in the soil. The boundary conditions for the PRECIS RCM are clear as an integral part of the system but this model comprises of very large amount of data (20-30 GB for a 30 year simulation), which need to be supplied separately. The LBCs from the global climate model (HadCM3Q) are used in this study to force the PRECIS simulations over a large domain that covers India and its neighbouring countries with six member ensembles from 17-member perturbed-physics ensemble (PPE) (HadCM3Q0-Q16, known as 'QUMP'). The model is calibrated and validated for India, which has boundaries at north of the equator between  $8^\circ 4'$  and  $37^\circ 6'$  north latitude and  $68^\circ 7'$  and  $97^\circ 25'$  east longitude as depicted in Fig. 1. The detailed descriptions about the QUMP ensemble members are given by Murphy et al. (2009), McSweeney and Richard (2010), and McSweeney et al. (2012).

### b. Model physics and dynamics

The model dynamics use a split-explicit finite difference scheme on an Arakawa 'B' grid (Arakawa and Lamb, 1977) in the horizontal and hybrid vertical coordinates. The prognostic

**Table 2.** Ensemble member selections based on their RMSE in reproducing summer monsoon rainfall over the wider Indian region for the present day climate simulations. Simulated data from the selected six members are evaluated with IMD observed data for the baseline period (1975-2005).

Ensembles	RMSE (mm d <sup>-1</sup> )	Temperature (Annual)		Summer Monsoon Rainfall (JJAS)		Winter Monsoon Rainfall (OND)	
		Max.Temp (°C)	Min.Temp (°C)	Mean (mm)	CV (%)	Mean (mm)	CV (%)
HadCM3Q5	0.696347	29.4	16.5	776	12	114	33
HadCM3Q	0.724145	28.7	16.5	865	9	152	23
HadCM3Q1	0.767074	29.5	16.3	633	19	13	35
HadCM3Q13	0.828461	29.5	17.1	846	9	131	27
HadCM3Q7	0.919369	29.5	16.9	791	11	129	29
HadCM3Q11	0.967986	29.6	17.4	837	8	133	29
IMD observed (1975-2005)		30.9	18.6	863	12	119	28

variables are surface pressure, zonal and meridional wind components, potential temperature and cloud-conserved temperature, and moisture at the 19 levels of atmosphere. A relaxation scheme as described by Davies and Turner (1977) is used to adjust the prognostic variables toward the boundary forcing in a zone of eight lateral grid boxes. All the prognostic variables in the RCM are relaxed towards the values interpolated in time from the data saved at every six hours from the GCM integration. The model, owing to its fine resolution, requires a time step of five minutes to maintain numerical stability. Heun advection scheme is used to avoid the complexity of time staggering (Mesinger, 1981). Major changes from earlier versions of HadCM3 include a new radiation scheme (Edwards and Slingo, 1996) and a parameterisation of momentum transfer by the convective processes (Kershaw and Gregory, 1997). The detailed description of PRECIS model components, such as its dynamical flow, the atmospheric sulphur cycle, clouds and precipitation, radiative processes, boundary conditions, initial conditions at the limits of the model domain, have been described in detail by Jones et al. (2004). In our study, a series of controlled sensitivity experiments were being carried out in order to determine the GCM boundary forcing and regional distributions of time averaged response by using a variety of ensemble members.

### c. Experimental set up

The LBCs are forced with estimated greenhouse gas and aerosol changes for the present day climate simulation period and then IPCC SRES A1B scenario as an external forcing for the future projections (2020s, 2050s and 2080s) is applied. In all of the ensemble members, the SRES A1B scenario (Nakićenović et al., 2000) is used to estimate future emissions. This scenario describes a world in which a rapid introduction of new and more efficient technologies with rapid economic development prevails and represents only one of the several possible futures considered in the 4th assessment report of the IPCC (Meehl et al., 2007). We looked at all the 17 members of the QUMP ensemble and employed climatological means of JJAS using model years 1975-2005 to represent the summer monsoon over India. We assessed precipitation bias by com-

paring precipitation dataset prepared by IMD for the same period, which shows generally wet bias over Himalaya and dry bias over the land during the summer monsoon (discussed in detail in the results section). Here our focus is to look for the models that demonstrate reasonable efficiency in simulating rainfall patterns over the focus region as well as the wider Indian subcontinent. Based on the root mean squares errors (RMSE) calculated for the entire region, the models are ranked as shown in Table 2, and the ranking indicates the models' bias in reproducing summer monsoon rainfall over the wider Indian region. Although biases were calculated for the entire region, we paid more attention at the model bias over our focus region. All model versions showed positive bias over this region. The magnitude of the biases was also similar except the model versions HadCM3Q0 and HadCM3Q7, which showed a relatively smaller bias. Therefore, we decided to go for a wider RMS error. The details of the model selections are described in one of our earlier publications, in which a similar methodology is applied only for the climate change projections for Tamil Nadu state of India (Prasanta Kumar Bal et al., 2016).

Based on the global performance of the model with respect to RMSE and the variety of changes in precipitation patterns, six ensemble members: HadCM3Q0, HadCM3Q1, HadCM3Q5, HadCM3Q7, HadCM3Q11, and HadCM3Q13 were chosen to represent a range of climate variations over the study region. The QUMP boundary datasets were derived from ERA40 [European Centre for Medium-Range Weather Forecasting (ECMWF)] reanalysis datasets available for the years 1957-2001 (Uppala et al., 2005; Simmons et al., 2007). The simulations followed the protocol set by IPCC Fourth Assessment Report (AR4) at 25 km × 25 km horizontal resolution over the whole India with transient runs of 130 years (1970-2100). We used geographical information system (GIS) technology to better understand the geographical problems at a regional scale. All the maps were developed by using Arc GIS tool with spatial interpolation methods and the trend analyses were performed using Mann-Kendall trend test at 0.05 significance level for Max.Temp., Min.Temp., and annual rainfall. In order to validate the model simulations, the daily rainfall data—developed by India Meteorological Department (IMD) and available for entire India for the period 1975-2005—were

used at a resolution of  $0.5^\circ \times 0.5^\circ$  (Rajeevan and Bhate, 2008). For mean Max.Temp. and mean Min.Temp., the IMD gridded data was also used at a resolution of  $1^\circ \times 1^\circ$  for the period of 1975-2005 (Srivastava et al., 2008). PRECIS simulated mean Max.Temp., mean Min.Temp. and annual rainfall were compared with the IMD observed data during the baseline period to understand the performance of the models. The spatial distribution of long-term mean rainfall during the South West monsoon/summer monsoon and North East monsoon/winter monsoon season were derived from six ensembles and compared with IMD observation data. The temperature anomalies were calculated by subtracting the mean from each observation. Similarly, the performance of rainfall change was calculated by taking the difference of future and observed values divided by the observed values from the model in percentage.

#### *d. Bias correction and applying Mann-Kendall method to downscaled data*

Observation data from IMD were compared with model simulated data for the period of 1975-2005 to ensure that the model can generate some realistic values with respect to the present day climatology of India. The model was evaluated to quantify biases. No RCM can represent perfectly the true climatology of a region. Therefore some calibrations are required to make the RCM output more realistic. In the bias correction method, we used the following equations to represent the relationship between present day simulations (Model simulated data for the period 1975-2005, distribution 1) and present-day observations (Observation data from IMD for the period 1975-2005, distribution 2). More details are given by Hawkins et al. (2012) and Ho et al. (2012).

$$O_{Fut} = \bar{O}_{ref} + \frac{\sigma_{o,ref}}{\sigma_{T,ref}}(T_{model} - \bar{T}_{ref})$$

where  $O_{Fut}$  = Future observation  
 $\bar{O}_{ref}$  = Mean of present day observation  
 $T_{model}$  = Model values for each year  
 $\bar{T}_{ref}$  = Mean of present day simulation  
 $\sigma_{o,ref}$  = Standard deviation of present day observation  
 $\sigma_{T,ref}$  = Standard deviation of present day simulation

Here it is assumed that the same relationship holds when future simulations are related to future observations.

Finally, for this study, we employed Mann-Kendall trend test at 0.05 significance level on the time series data for the whole India for a baseline period of 1975-2005 and the future periods of 2020s, 2050s and 2080s. According to this test, the null hypothesis  $H_0$  holds that there is no trend and the alternative hypothesis  $H_1$  holds that there is a trend. While rejecting the null hypothesis, the results seemed to be statistically significant. The detailed procedures and methods on the Mann-Kendall test are discussed by Önöz and Bayazit (2012) and Gilbert (1987).

### 3. Results

PRECIS showed quite reasonable and statistically significant performance in assessing temperatures and rainfall with IMD observed dataset for the present day climate simulation for the whole India. We find good agreement between the observed and simulated climatological Indian monsoon rainfall distribution, for coefficient of variation (CV), mean and standard deviation during the present day climate simulation period. Table 2 shows the mean Max.Temp., Min.Temp. and seasonal rainfall averaged over the country (only land points) and their CV. HadCM3Q0 ensemble mean rainfall during the monsoon seasons is however very close to the observed mean rainfall. All other means except the HadCM3Q1 means are very close to the observed values. Similarly, all the ensembles except HadCM3Q1 model exhibit much smaller CV compared to the observation. The CV of all the ensembles ranges from 9-12%, which is very close to the observed CV of 12% during JJAS and during OND, the CV of ensembles ranges from 23-35% compared to the IMD observed data that equal to 28%. If the CV is high, the relative variations among the datasets are also high. Therefore if CV is higher, the dispersion in the inter-annual rainfall variability during the observed OND period would be greater compared to the JJAS period. We also examined the performance of the ensemble members while presenting the comparison of the climatological mean and standard deviation of annual temperatures and rainfall with the observation during the period 1975-2005. Simulated average annual Max.Temp. from the six ensembles ranges from 28.7-29.6°C and Min.Temp. ranges from 16.3-17.4°C where as the observed datasets from IMD show 30.9°C and 18.6°C for Max. Temp. and Min.Temp., respectively. The standard deviation of Max.Temp. Min.Temp. and annual rainfall from the six ensembles ranges between 0.58-0.76°C, 0.39-0.64°C and 100-156 mm are very close to the IMD datasets which show 0.66°C, 0.26°C and 107 mm for the temperatures and rainfall, respectively. The map-to-map comparisons between the observed and model simulated rainfall and temperature fields show realistic results by representing the present climatology of India. In addition, trend analyses in the time series datasets for the simulated averaged annual temperatures and rainfall show significance at 95% confidence level. Therefore it can be said that PRECIS performs quite reasonably and produces statistically significant results while assessed with IMD observed dataset for the whole India. The state wise temperatures and rainfall change projections with respect to the present day climate simulations are given in Table 3. On the basis of the results from Mann-Kendall trend test, the null hypothesis can be rejected for most of the ensemble members as significant increasing trends are indicated for the future projections for temperatures over India, and the p values (Table 4) are less than the significance level  $\alpha$  (alpha) = 0.05. On the other hand, in case of future projections for rainfall, the increasing trends are not significant in some of the ensemble members as p values are greater than the significance level  $\alpha$  (alpha) = 0.05.

**Table 3.** State wise future climate change projections: Change in Max.Temp. (°C), Min.Temp. (°C) and annual rainfall (% change) projections for 2020s, 2050s and 2080s with reference to baseline (1975-2005).

State Name	Max.Temp. Change (°C)			Min.Temp. Change (°C)			Annual Rainfall Change (%)		
	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
West Bengal	1.0	2.2	4.1	1.0	2.3	3.9	5.1	11.5	2.2
Orissa	1.0	2.0	3.4	1.1	2.3	3.7	4	14.8	19.3
Andhra Pradesh	1.0	1.9	3.1	1.0	2.3	3.5	1	7.8	7.1
Tamil Nadu	1.1	2.0	3.1	0.9	2.1	3.3	-9.4	-5	-2.7
Kerala	1.0	1.9	2.8	0.9	2.0	3.0	5.8	6.4	5.9
Karnataka	1.1	2.0	3.1	1.0	2.3	3.5	4	7.7	6.4
Goa	0.8	1.7	2.4	0.9	2.0	2.9	2	5.2	6.1
Maharashtra	1.0	2.0	3.0	1.1	2.4	3.6	6.2	23.1	21.4
Gujarat	0.6	1.9	2.7	0.9	2.3	3.5	13.2	13.2	23.1
Madhya Pradesh	1.0	2.1	3.3	1.1	2.5	3.8	1.8	9.6	16.7
Bihar	1.0	2.3	4.2	1.0	2.3	3.9	1.4	12	7.1
Uttar Pradesh	0.9	2.5	3.9	0.9	2.5	3.9	1.4	8.2	10.9
Rajasthan	0.6	2.1	3.2	0.9	2.6	3.9	6.6	3.9	9.1
Haryana	0.5	2.2	3.4	0.8	2.6	3.8	4.5	6.7	13.6
Punjab	0.4	2.2	3.2	0.8	2.6	3.7	6.7	6.5	23.4
Himachal Pradesh	0.9	2.4	3.5	1.0	2.6	3.8	1.5	10.2	25.5
Jammu & Kashmir	0.8	2.4	3.4	1.2	2.8	4.1	9.7	10.3	26
Sikkim	1.0	2.3	3.9	0.9	2.4	3.8	1.1	6.1	6.2
Assam	0.9	2.2	3.6	0.8	2.1	3.3	2.8	8	16.2
Tripura	0.8	2.1	3.8	0.9	2.1	3.5	4.4	10.2	1.2
Mizoram	0.8	2.0	3.5	0.8	2.0	3.4	5.9	5.4	12.7
Manipur	0.8	2.0	3.3	0.8	2.1	3.4	2.6	9.9	19.5
Meghalaya	0.8	2.1	3.6	0.8	2.1	3.4	4	10.7	9.1
Nagaland	0.8	2.0	3.2	0.8	2.1	3.3	1.7	11.3	20.5
Arunachal Pradesh	0.9	2.2	3.5	0.8	2.1	3.3	8	4.5	13.8
INDIA	0.9	2.1	3.4	0.9	2.3	3.6	4	9	13

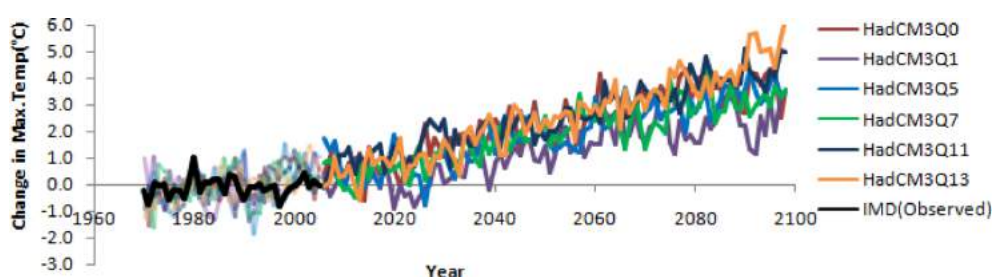
### a. Temperatures projections

PRECIS simulation in the present study indicates an all-round warming over India associated with increasing greenhouse gas concentrations. India's average annual surface air maximum temperature may go up by 3.4°C by the end of the century with respect to the baseline. The temperature would intensify more by the end of the century in the range of 2.3°C to 4.0°C (Fig. 2). A general maximum increase of 3.4-5.0°C is projected over the north central part of India including the states of Bihar, West Bengal, Uttar Pradesh, while some of the peninsular and North West part of India including the states of Andhra Pradesh, Goa, Kerala, Gujarat, Maharashtra show the minimum increase of 2.4-3.1°C (Fig. 3), by the end of the century. Analyses of the climatic zone wise projections generally indicate a slight increasing tendency from coastal area to the interior. This is due to the fact that the influence of the ocean is

manifested over the coastal areas and therefore the coastal areas respond slowly to the anthropogenic climate change. On the other hand, due to rapid growth in urban agglomeration and industrialisation, the interior land areas are more sensitive to the climate change and a warming contrast from the coastal to interior land regions is quite apparent in the future changes. North Central, North East and Northern Hilly regions may face maximum increase in temperature change of 3.5-3.8°C by the end of the century and a minimum increase of 2.9-3.1°C over Peninsular, West Central and North West zones of India. Furthermore, during March-May (MAM), all the models projected maximum increase of 4°C in temperature change over West Central and North Central regions, which comes to above 44°C when compared to the baseline period which is above 40°C. In particular, all the models projected an average increase in temperature change of 3°C which would be above 41°C by end of the century when compared to the baseline which is above

**Table 4.** Results of the Mann-Kendall trend analysis for temperature and rainfall data from all the six ensemble members for the whole India at 0.05 significance level.

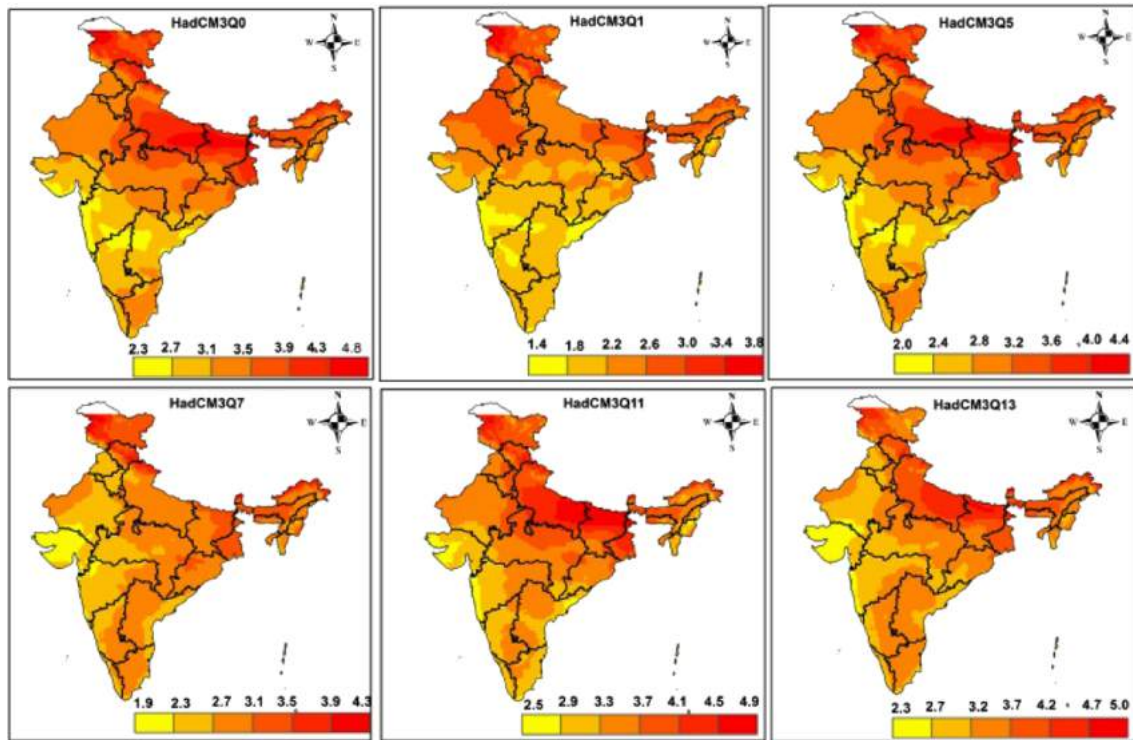
Model	Kendall's tau				p-value (two tailed test)			
	Present 1975-2005	2020s	Future 2050s	2080s	Present 1975-2005	2020s	Future 2050s	2080s
Max.Temp.								
IMD	0.10	--	--	--	0.43	--	--	--
HadCM3Q0	0.11	0.45	0.35	0.27	0.11	0.000	0.005	0.02
HadCM3Q1	0.006	-0.016	0.11	0.31	0.14	0.72	0.000	0.14
HadCM3Q5	0.09	0.37	0.56	0.36	0.000	0.91	0.37	0.001
HadCM3Q7	0.01	0.43	0.45	0.51	0.09	0.003	< 0.0001	0.003
HadCM3Q11	0.004	0.42	0.47	0.62	0.01	0.000	0.000	< 0.0001
HadCM3Q13	0.14	0.04	0.45	0.18	0.000	0.001	0.000	0.14
Min.Temp.								
IMD	0.09	--	--	--	0.50	--	--	--
HadCM3Q0	0.40	0.45	0.48	0.37	0.002	0.000	0.000	0.003
HadCM3Q1	0.54	0.43	0.52	0.25	0.54	< 0.000	< 0.0001	0.05
HadCM3Q5	0.41	0.15	0.22	0.49	0.41	0.24	0.081	< 0.0001
HadCM3Q7	0.68	0.79	0.72	0.55	0.68	< 0.0001	< 0.0001	< 0.0001
HadCM3Q11	0.52	0.65	0.62	0.54	0.52	< 0.0001	< 0.0001	< 0.0001
HadCM3Q13	0.53	0.58	0.62	0.73	0.53	< 0.0001	< 0.0001	< 0.0001
Annual Rainfall								
IMD	-0.01	--	--	--	0.94	--	--	--
HadCM3Q0	-0.10	0.06	0.24	0.23	0.43	0.6	0.05	0.06
HadCM3Q1	0.16	0.05	-0.22	0.08	0.21	0.6	0.08	0.48
HadCM3Q5	0.09	0.13	0.25	0.21	0.47	0.3	0.04	0.08
HadCM3Q7	0.02	-0.06	0.05	0.16	0.88	0.6	0.67	0.19
HadCM3Q11	0.28	0.05	0.16	0.05	0.02	0.6	0.20	0.69
HadCM3Q13	0.16	0.05	0.24	0.04	0.21	0.98	0.06	0.72

**Fig. 2.** Time series of surface air temperature change (°C) (Max.Temp. anomalies, relative to the present day climate) from the various ensemble members for the scenarios A1B. Values are annual means averaged over the whole India for the period 1975-2100. The black solid lines shows the values based on the gridded India Meteorological Department (IMD) temperature data.

38°C; this indicates harsh summers in the North and North-West regions of the country including all the climatic zones except Northern Hilly zone. The temperatures in the West Central and North Central regions are generally appearing as most highest warm areas in the future by most of the models

for the period between March and May. Most of the models captured similarly the different seasonal temperature cycles in the different climate zones in India (Fig. 4). Model HadCM3Q13 tends to be consistently the warmest model and HadCM3Q1 the coolest one. Figure 5 shows climatic zone wise Max.Temp.





**Fig. 3.** Projected future changes in annual maximum temperature ( $^{\circ}\text{C}$ ) by end of the century with respect to baseline period in a spatial scale for different projections by the ensemble members with a range of variations.

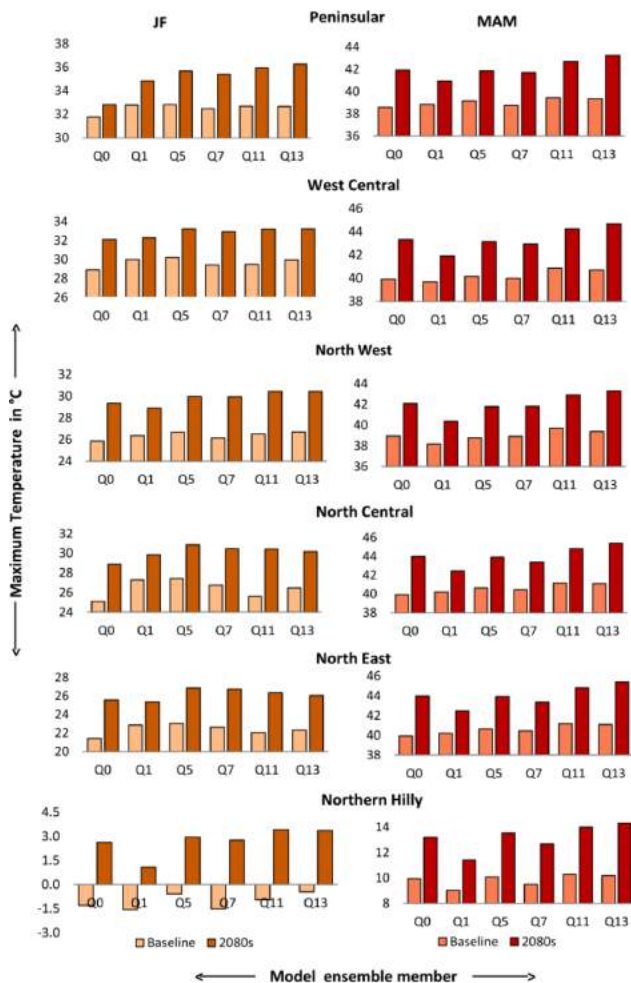
Projections during JJAS and OND seasons by the end of the century when compared to the baseline. In Figs. 4 and 5, the naming conventions of the ensemble members are shown in short. For example, HadCM3Q0 is shown as Q0 and so on. Our analyses show that during JJAS period, all the models projected an average increase in temperature above  $32\text{--}35^{\circ}\text{C}$  over all the climate zones except North West and Northern Hilly zones for that the Max.Temp. and Min.Temp. values are  $38.1$  and  $21.5^{\circ}\text{C}$  respectively by the end of the century, in contrast to the baseline values, which are above  $30\text{--}32.8^{\circ}\text{C}$  for all the zones except North West and Northern Hilly zones, where the values are  $35.6^{\circ}\text{C}$  and  $18.1^{\circ}\text{C}$ , respectively. Projections of annual mean Max.Temp. over India as a whole for 2020s, 2050s and 2080s with reference to the baseline period indicate an average increase of  $0.9^{\circ}\text{C}$ ,  $2.1^{\circ}\text{C}$  and  $3.4^{\circ}\text{C}$ , respectively at the emission rate of A1B. In a similar way, the projections of annual mean Min.Temp. over India as a whole for 2020s, 2050s and 2080s with reference to baseline indicates an average change of  $0.9^{\circ}\text{C}$ ,  $2.3^{\circ}\text{C}$ ,  $3.6^{\circ}\text{C}$  respectively. Figure 6 shows the Min.Temp. anomaly over India for the period 1970-2100 based on IMD gridded data. It shows a linear trend of  $3.7^{\circ}\text{C}$  increase for the future 100 years with reference to the baseline. The temperature intensifies more by the end of the century in the range of  $2.8^{\circ}\text{C}$  to  $4.7^{\circ}\text{C}$  for different projections. The greenhouse gases have a higher impact at night time when they absorb infrared radiation and reduce the cooling, and this effect is more intense than the daytime warming. Therefore the increase in minimum tem-

perature is more rapid than the maximum temperature. Further, there is a negative trend in the diurnal temperature range (result is not shown) during the end of the century which indicates that the minimum temperatures are warming faster than the maximum temperatures.

### **b. Rainfall projections**

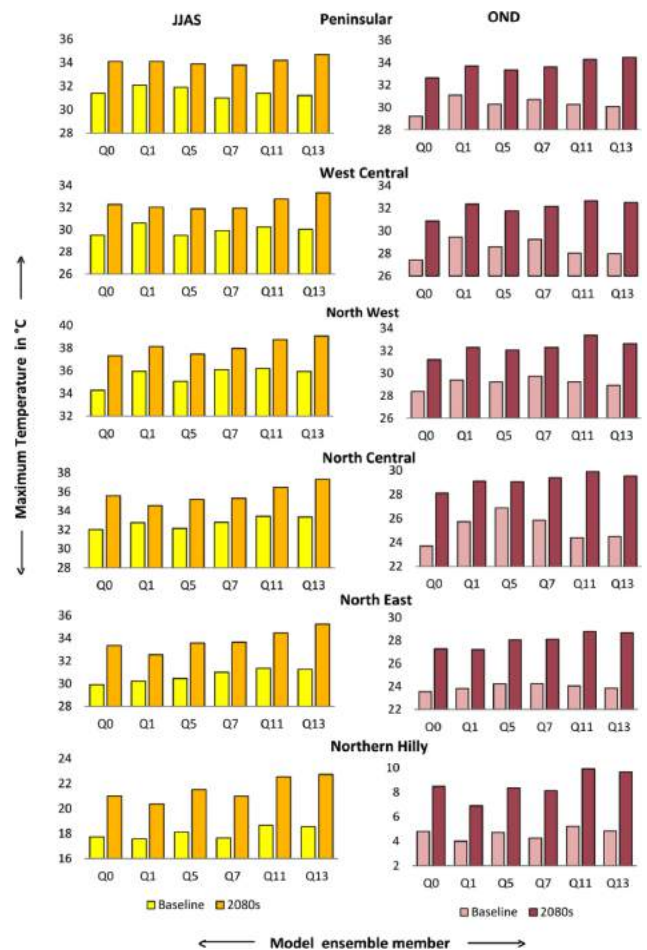
The important features of the mean monsoon are the climatological mean rainfall and circulation over India during the summer (JJAS) and winter (OND) monsoon seasons. Figures 7 and 8 show the model evaluations with the IMD observed values during the period of 1975-2005 for JJAS and OND, respectively, over India. All the models show acceptable efficiency while capturing rainfall patterns at a spatial scale but some of the models under-estimate summer monsoon rainfall when compared to actual observation but it is simulated with a better spatial distribution, especially the regional orographic precipitation patterns. The values determined by the model ensembles are almost near to the IMD observed rainfall values, which show an average precipitation of  $863$  mm during JJAS and  $119$  mm rainfall during OND for the whole country. We find a good agreement between the observed and simulated climatological Indian monsoon rainfall distribution for the period of 1975-2005. The distribution during the JJAS period shows that maximum rainfall over Western Ghats, central India and north eastern area. Over the central parts of India, the rainfall increases from west to east. The spatial patterns of





**Fig. 4.** Comparisons of the seasonal average temperature (°C) during JF (Jan-Feb) and MAM (Mar-May) periods obtained from different model projections over the whole India (climatic zone wise) towards the century end, relative to present day simulations. Six members of the QUMP ensemble are shown in order to produce the possible range of variations in the future projections.

ensembles show the maximum rainfall along the west coast of India, foot hills of Himalaya, eastern Arabian Sea, south equatorial Indian Ocean and North Bay of Bengal. Similarly during OND season, all the six ensembles show less rainfall over the whole India except for the state of Tamil Nadu. Being located on the lee ward side of the Western Ghats, Tamil Nadu gets only about 32% of the annual rainfall during the JJAS period. During the principal rainy season, the OND period, it receives about 55% of the annual total rainfall. Though the ensembles show similar spatial patterns as the observations, all the ensembles underestimate the observed rainfall during the JJAS and OND. The seasonal precipitation patterns in the baseline simulation match well with the observed ones; this indicates an adequate representation of present-day climate conditions. However, there exist some quantitative biases in the spatial patterns. The projected annual rainfall change shows some increase by 2020s, 2050s and 2080s by 2-6%, 7-



**Fig. 5.** As in Fig. 4, but for JJAS and OND.

12% and 15-24% respectively, when compared to baseline. Figure 9 indicates that there is clear trend in rainfall change over India in the next 100 years based on IMD gridded data. As far as the future rainfall trends are concerned, all the models show positive trends indicating increase in annual rainfall by 12-20% for different projections. The projected summer monsoon rainfall change shows a significant correlation with the ensemble simulations that actually project average increase in rainfall of about 12-30% over the whole India and of about 25-50% over west coast and west central India including the states of Madhya Pradesh and Maharashtra and some part of Orissa at end of century (Fig. 10). For India as a whole, all the models estimate 20-35% increase in winter monsoon rainfall in future scenarios by the end of the century with respect to the present day climate (Fig. 11). Spatial patterns of rainfall change from most of the ensembles indicate maximum increase over west coast, central and northeast region. Rise in rainfall can be seen over all the states except Tamil Nadu and some of the western parts of India which show slight decrease in precipitation in the future scenarios. Based on the rainfall intensities, we classified the daily rainfall into different categories: viz. i)  $10 < \text{Rainfall} \leq 12$  mm, ii)  $12 < \text{Rainfall} \leq 14$  mm, iii)  $14 < \text{Rainfall} \leq 16$ , iv)  $16 < \text{Rainfall} \leq$

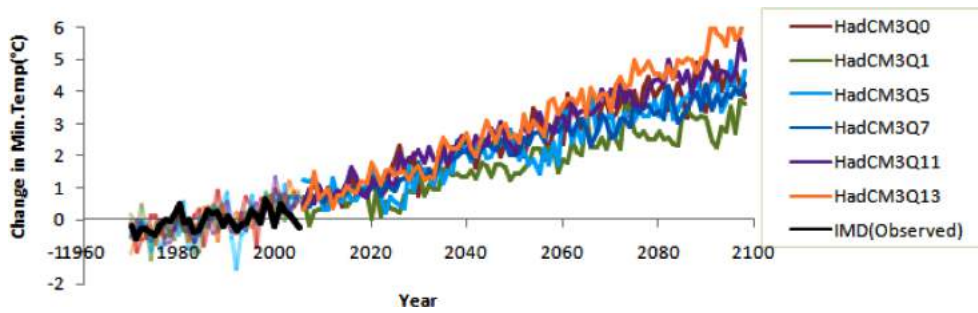


Fig. 6. Min.Temp. anomaly (°C) over the whole India for the period 1975-2100 with respect to the present day climate. The black solid lines show the values based on the gridded IMD Min.Temp. data.

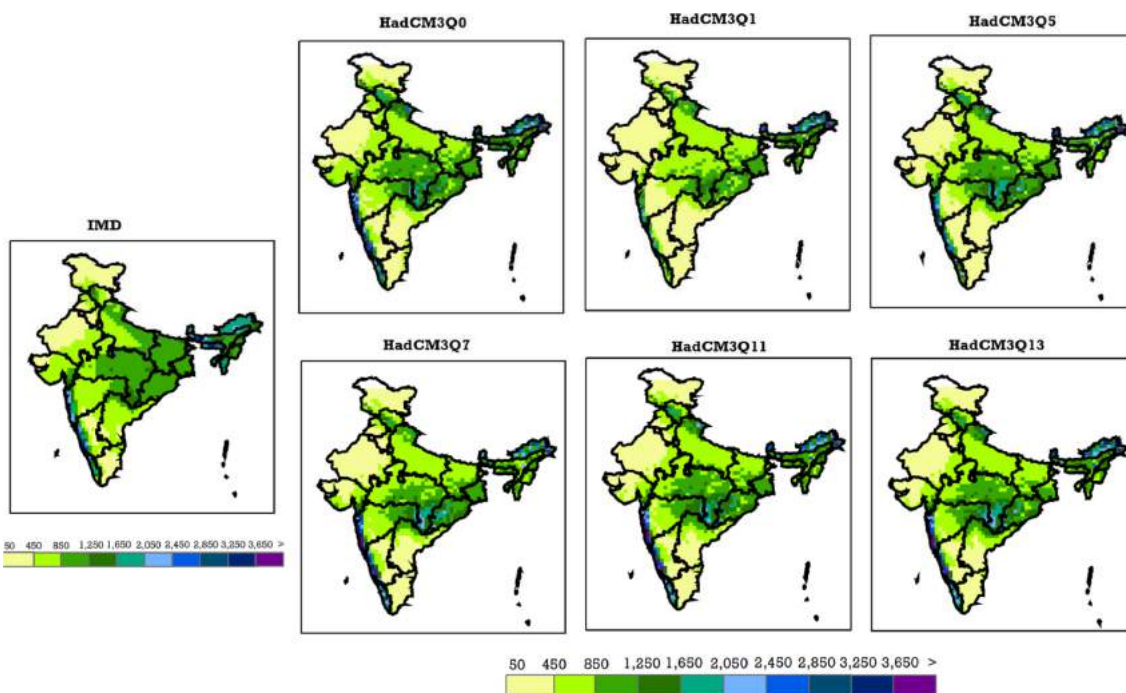


Fig. 7. Observed and simulated (baseline) patterns of summer monsoon (Jun-Sep) precipitation (mm) for PRECIS during the period 1975-2005 over the whole India. The observed monsoon rainfall climatology is based on the gridded IMD rainfall data.

18 and v) Rainfall > 18 mm. The analyses of frequency distributions of daily rainfall show that during JJAS, the number of days with rainfall below 10 mm d<sup>-1</sup> indicates a decrease of 5-8% by the end of the century while the number of days of rainfall above 10 mm d<sup>-1</sup> and 18 mm d<sup>-1</sup> indicates an increase of 2-5% over the whole India (Fig. 12a). Rainfall above 18 mm d<sup>-1</sup> shows an increase of 5% at the baseline by the end of the century. The number of days is 10, but in future it is as high as 60 (50 days more when compared to baseline). As per the projections of OND, the number of days with rainfall from 0 to 2 mm d<sup>-1</sup> indicates a decrease of 5% by end of the century (72% of the total number of rainy days) when compared to the baseline period (67% of the total number of rainy days) and rainfall above 8 mm d<sup>-1</sup> indicates 5% increase by the end of the century from the baseline (45 total number of rainy days in

baseline and 145 days in future period) as shown in Fig. 12b.

*c. Evaluation of the bias correction method applied to downscaled precipitation and temperature data*

A few of the model output values are poor in simulating the temperature and rainfall distributions over the whole India. This indicates that after applying the bias correction method, the model generated temperature and rainfall outputs are reasonably consistent with the observed data at the annual scale. Hence, the result suggests applying a bias correction methodology for calibrating temperatures and annual rainfall over India. The results are shown in Figs. 13 and 14. Future temperature and rainfall changes are investigated after correcting the biases in the models. The bias uncorrected predictions

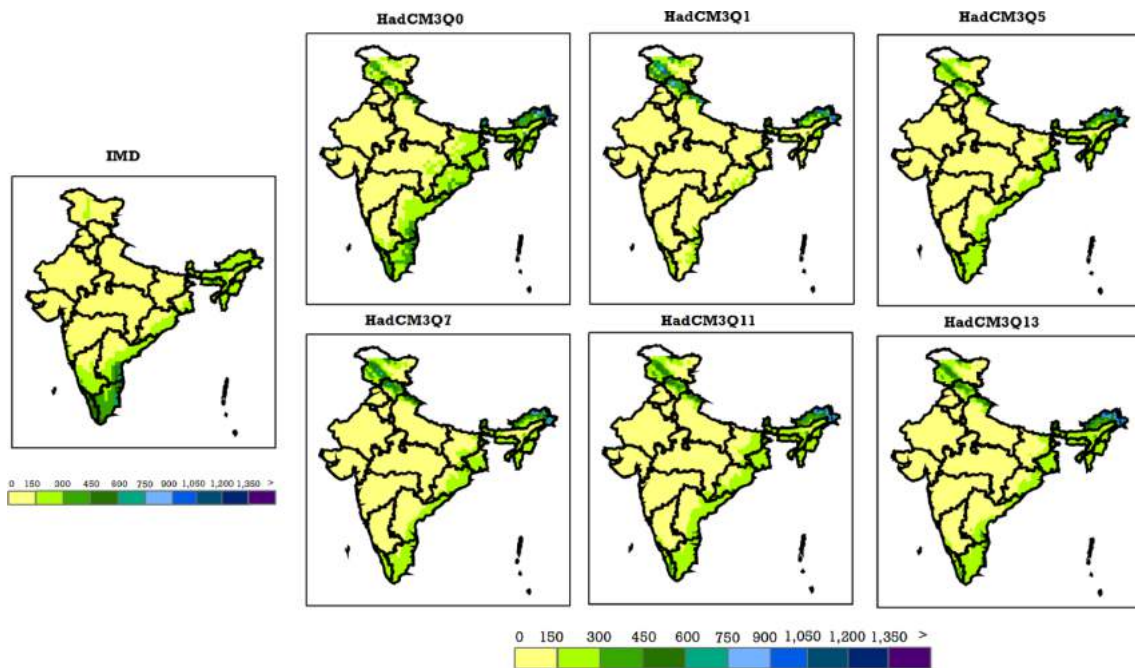


Fig. 8. As in Fig. 7, but for OND.

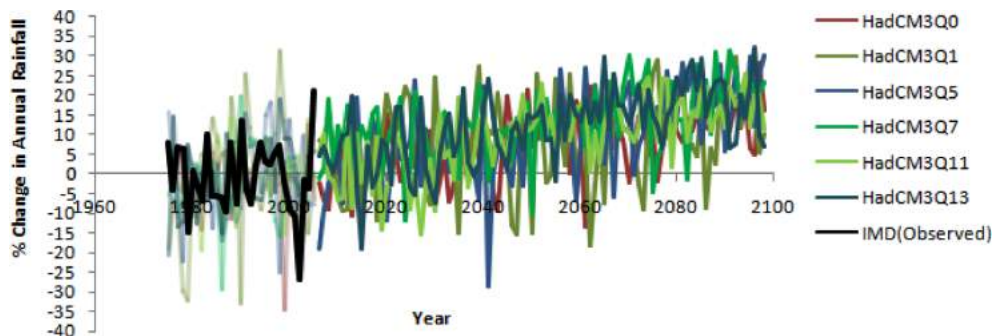


Fig. 9. Rainfall anomaly (% change) averaged over the whole Indian region for the period 1975-2100 with respect to the present day climate. Projections are shown from the different ensemble members with a range of variations. The black solid lines shows the values based on the gridded IMD annual rainfall data.

generated a temperature change of 2.9-4.2°C by the end of the century with respect to the baseline, whereas the bias corrected results are within the range 2.1-4.5°C. Similarly in case of total precipitation, the results for the total changes are within the range of 15-24% before the correction and 9-27% after the correction for the same period (Table 5). The values are not very important within the actual projected range, as obtained by all the models before correction due to the smaller deviations. As the averages from a longer simulation period (i.e., 1975-2005, 2005-2035, 2035-2065 and 2065-2095) are considered, it is observed that the performance of PRECIS increases by reducing the underestimation in case of temperature and rainfall calibrations. The climate change assessments were done for both temperature and precipitation by comparing model generated baseline data with model generated future data. On the basis of the studies of Maraun (2012),

Ehret et al. (2012), and Teutschbein and Seibert (2013), a common assumption can be made that the stationarity of the model bias implying that the empirical relationships in the correction algorithm and its parameterisation for the current climate conditions do not change over time and are also valid for future climate conditions. Therefore, the future climate change assessments in this study are performed by ignoring the model biases.

**d. Model performances and uncertainty in downscaling**

The response of the summer monsoon over the Indian region towards the enhanced greenhouse gases have previously been analysed by Rupa Kumar and Ashrit (2001), May (2011), Kripalani et al. (2007), Annamalai et al. (2007), Turner (2011), Dobler and Ahrens (2010, 2011), Cherchi et al. (2011), and



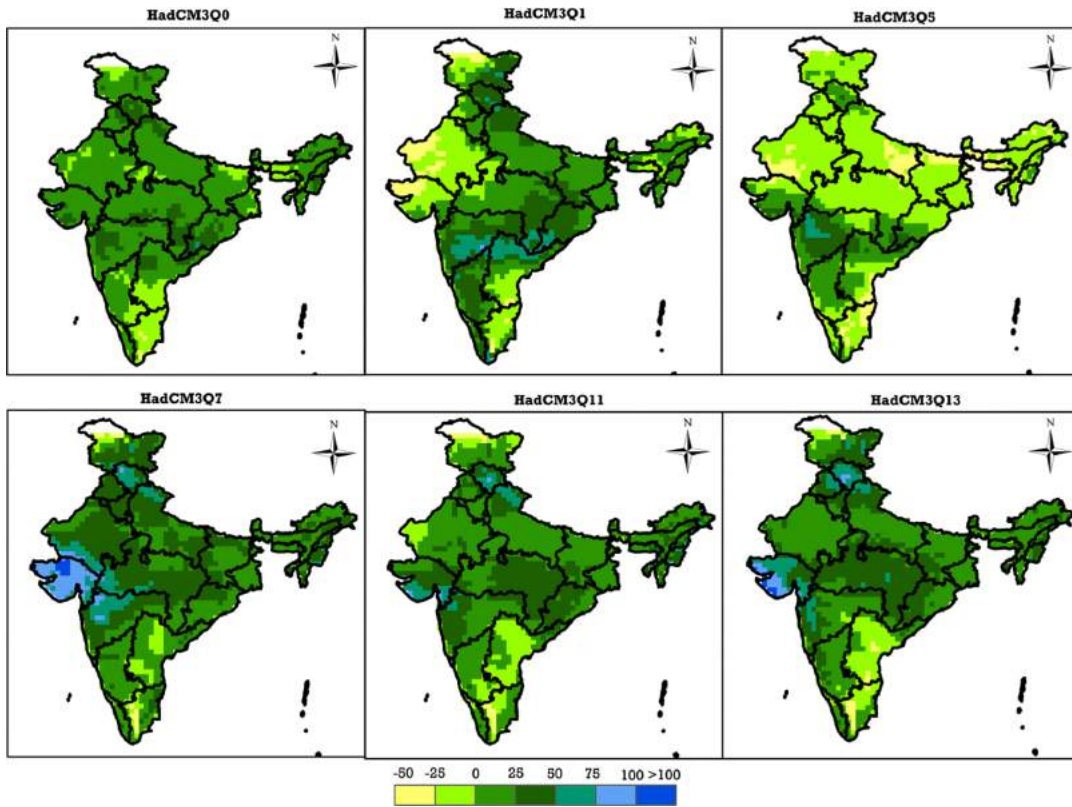


Fig. 10. Projected changes in summer monsoon precipitation (JJAS) towards the end of 21st century compared with baseline period 1975-2005.

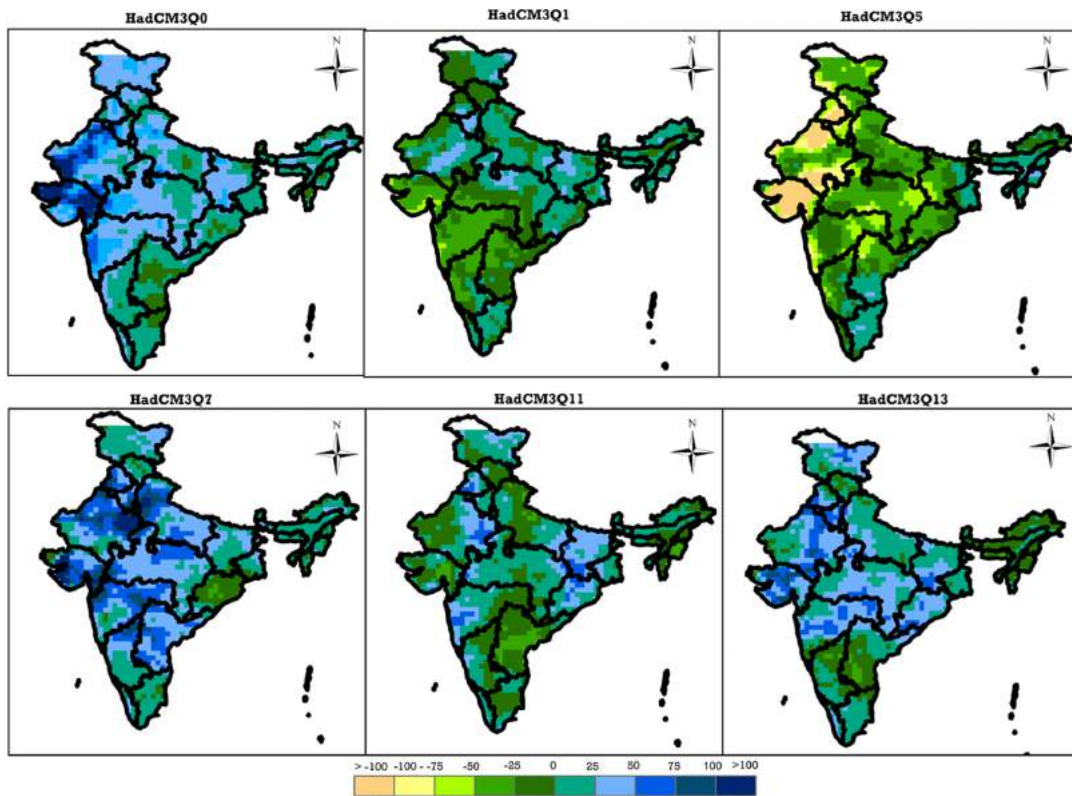


Fig. 11. As in Fig. 10, but for winter monsoon precipitation (OND).

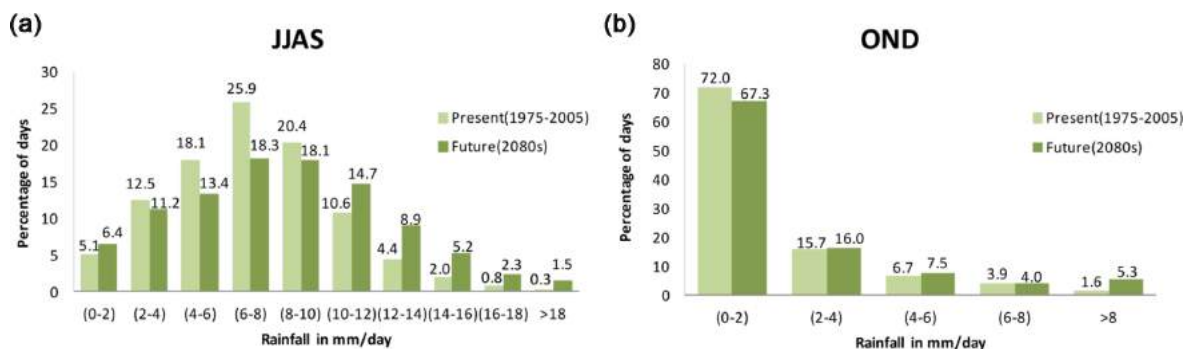


Fig. 12. Frequency distribution (% of days) for the daily rainfall events over the whole India during (a) JJAS (Jun-Sep) and (b) OND (Oct-Dec) periods.

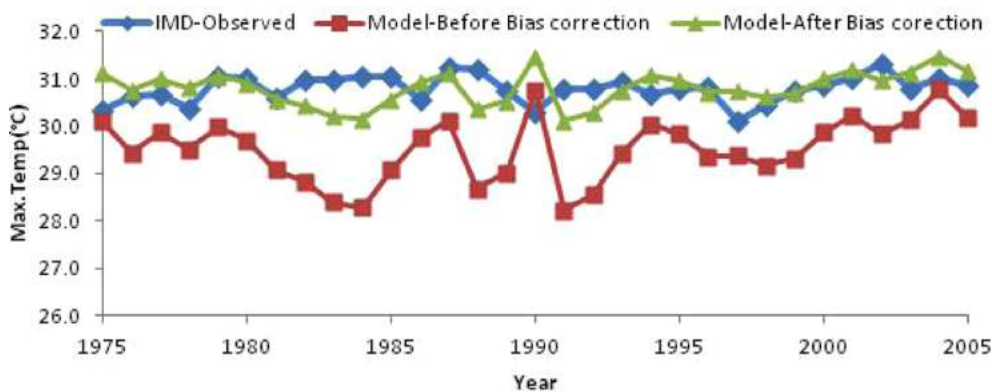


Fig. 13. Bias correction for the annual Max.Temp. over the whole India during 1975-2005.

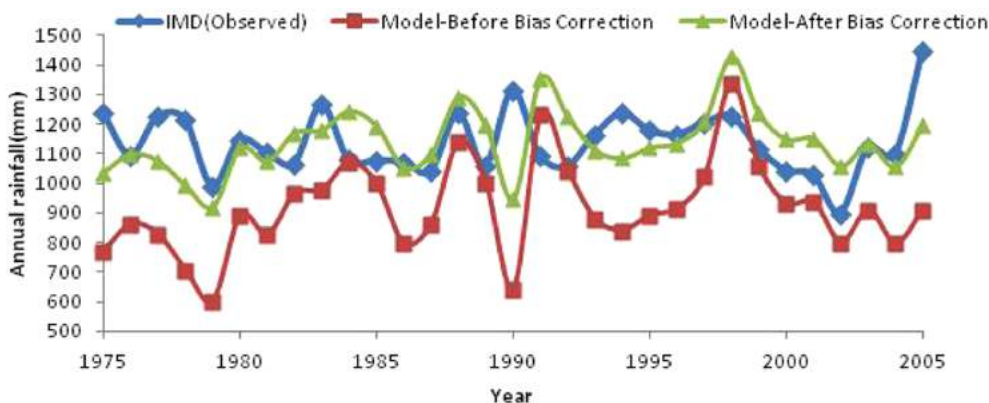


Fig. 14. Bias correction for the annual precipitation over the whole India during 1975-2005.

Turner and Annamalai (2012) by using different climate modelling approaches. The results of these studies show an improvement in the simulation of spatial and temporal distribution compared to the coarser global models. Results from the above climate modelling studies also suggest intensification of Indian summer monsoon rainfall in future warmer climate due to increase in green house gas concentrations. A similar study by Rupa Kumar et al. (2006) also shows that the annual mean surface air temperature may rise by the end of the

century in a range of 3-5°C in A2 scenario and 2.5-4°C in the B2 scenario by using PRECIS RCM, while another study by Kumar et al. (2013) reports that the PRECIS RCM projection over India using the SRES A1B scenario indicates a rise in temperature around 2.5-5.5°C with a maximum over Himalaya, North, Central and West India and a significant increase of rainfall over peninsula (20-40%) and Western Ghats and North East regions (10-20%) by the end of the 21st century. Rajendran and Kitoh (2008) also used high resolution global model to

**Table 5.** Results for the projected changes for temperature and rainfall data from all the six ensemble members for the whole India before and after the bias correction method.

Model	Before Bias Correction			After Bias Correction		
	2020s	2050s	2080s	2020s	2050s	2080s
Temperature projections (change in °C)						
HadCM3Q0	1.0	2.3	3.5	1.1	2.5	3.8
HadCM3Q1	0.6	2.0	3.1	0.5	1.6	2.6
HadCM3Q5	0.7	2.0	2.5	0.6	1.9	2.7
HadCM3Q7	1.3	2.4	3.8	1.3	2.5	4.0
HadCM3Q11	0.9	2.5	4.4	1.0	2.7	4.4
HadCM3Q13	0.2	1.4	2.3	0.2	1.3	2.1
Annual rainfall projections (% change)						
HadCM3Q0	2%	10%	15%	3%	12%	17%
HadCM3Q1	8%	10%	16%	4%	5%	9%
HadCM3Q5	5%	10%	21%	4%	9%	18%
HadCM3Q7	9%	14%	24%	10%	16%	27%
HadCM3Q11	2%	13%	20%	2%	16%	25%
HadCM3Q13	6%	15%	23%	6%	15%	23%

study the impact of warming on Indian monsoon and their results show that there is a widespread increase in rainfall in the interior parts of India but a reduction in rainfall over the coastal states. Krishnakumar et al. (2011) also investigated the future pulse of Indian summer monsoon by using high resolution climate model PRECIS simulated at 50 km resolution under A2 scenario. Their results indicate an increased probability of longer extreme temperature spells and a general increase in the extreme precipitation amounts in the future. They found a good agreement between the observed and simulated climatological Indian monsoon rainfall distribution, its annual cycle, standard deviation, and sensitivity to El Niño-Southern Oscillation.

In this paper, we have used the PPE approach, which is used to produce a range of future climate predictions based only on one climate model instead of using multi-model ensemble (MME) approach where many modelling centres contribute their GCM simulations to generate the range of future climate predictions (Jones et al., 2012). Perturbed members HadCM3Q1-HadCM3Q16 are ranked according to the values of their global climate sensitivity, and HadCM3Q1 showed the lowest climate sensitivity in response to a given increase in atmospheric CO<sub>2</sub>, and HadCM3Q16 showed the highest. This is inherently linked to the experimental design of the QUMP ensemble, in which the topmost ensemble members (i.e. Q16) depict the highest climate sensitivity (i.e. they show the highest warming) and vice versa. Though the simulations of all the six models for the present day climate show more variations. The mean values for temperature and rainfall averaged over the whole India are similar for all the models. Among the six ensemble members, HadCM3Q1 shows the poorest performance while simulating the present day climatology of India though we selected this ensemble to quantify the variations.

Although the model shows poor performance during the current climate baseline period but it can be assumed that it may simulate well the future climatology of India.

There have been several research papers on downscaling, uncertainty in the GCM forcings and RCM-based studies (McGregor, 1997; Giorgi and Bi, 2000; Wang et al., 2004a; Julien et al., 2011; McGregor, 2013; Hong and Kanamitsu, 2014). These studies have reviewed the current state of methods related to dynamical downscaling and various uncertainty assessments to monitor the future climate changes. However, uncertainties in the large-scale fields provided by the GCM are still open to questions. These preliminary results enabled us to provide future climate change information for India by assessing the regional climate variability that is embedded in large-scale conditions and related to regional mechanisms. This high resolution climate change information will be useful for the various stakeholders and policymakers in India to formulate different adaptation strategies to cope with future climate change. However, there are limitations in our approach in assessing the uncertainty in projected climate by perturbed physics in GCM data, even if the boundary conditions are perfectly known and many ensemble simulations are being assessed taking the uncertainties in the initial conditions into account. In future work, it can be useful to consider the influence of GCM boundary forcing and associated circulation changes in order to study the uncertainty assessments which are mostly attributed to the physical parameterisations of atmospheric convection, cloud microphysics, planetary boundary layer, radiation and also to the inherent properties of the domain boundaries, horizontal and vertical resolutions of the forcing, surface conditions and atmospheric lateral forcings, which strongly affect the simulated climate. Further, we believe that simulations of more regional climate



models with more ensemble members from different organisations of the world will provide a better understanding of how the difference in model formulation can lead to uncertainty in the projections. Besides this, in future, CMIP5 coupled climate model simulations and their projections in which uncertainties in physical and biogeochemical feedback processes can be explored more systematically may be expected to provide a better advice on future regional changes over India. In particular, ensembles of PRECIS projections will be needed to provide a more comprehensive survey of possible future changes and their relative likelihoods of occurrence.

#### 4. Summary and conclusions

This study considered various aspects of simulation results by employing the high resolution PRECIS RCM with perturbed physics ensemble approach. This model appeared quite reasonable in simulating the mean and annual cycle of the temperature and rainfall for the present day climate simulations over the Indian region. Future climate predictions of India show a warmer condition with increase of maximum temperature, minimum temperature and an intensification of the precipitation cycle. Model simulations under A1B scenarios of increasing greenhouse gas concentrations and sulphate aerosols indicate an increase of 2.5-4.4°C in day time (Max.Temp.) and 2.8-4.7°C during night time (Min.Temp.) temperatures towards the end of the 21st century for different projections. For the whole country, the projections of annual rainfall show an increase of 15% to 24% by the end of the century when compared to the present day climate simulations. Maximum expected increase in rainfall is projected over the West Coast, and central and northeast regions of India. Projections of summer monsoon rainfall show substantial increases of about 25-50% over a large area including West Central region. Extreme rainfall events also indicate an increase of 2-5% over the whole India. Additionally, the time trends of the annual indices were analysed for a selected set of 30 years from the simulated datasets. The trends were derived from linear regression and local statistical significances at the 95% confidence level were established using the Mann-Kendall test. We tried to predict the possible range of variations using best six ensemble members from PRECIS. The ensemble simulations for India show reasonable efficiency in simulating temperature and rainfall patterns for the region. However, limitations still exists in our approach while assessing the projected climate by perturbed physics in GCM data. We validated the model data by employing a bias correction methodology for correcting the projected temperature and precipitation bias but the bias corrected results show no significant differences compared to the uncorrected bias results while assessing the future climate changes. Finally, the projected climate changes are likely to have large impacts on various sectors such as agriculture, water resources, health, habitat, etc. This might have severe consequences if certain

actions are not taken by the various policy makers, stake holders and government bodies by formulating various adaptation strategies on environmental protection.

**Acknowledgements.** The authors are thankful to the 'Hadley Centre for Climate Science and Services, Met Office, United Kingdom', for making available the PRECIS and the LBC data for the simulations used in this study and Centre for Climate Change and Adaptation Research would like to take this opportunity to acknowledge Department of Environment, Government of Tamil Nadu for the vision and foresight which inspired the centre to initiate the climate change research.

**Edited by:** Song-You Hong, Kim and Yeh

#### REFERENCES

- Annalai, H., K. Hamilton, and K. R. Sperber, 2007: The South Asian Summer Monsoon and Its Relationship with ENSO in the IPCC AR4 Simulations. *J. Climate*, **20**, 1071-1092, doi:<http://dx.doi.org/10.1175/JCLI4035.1>.
- Arakawa, A., and V. R. Lamb, 1977: Computational design of the basic dynamical processes of the UCLA general circulation model. *Methods in Computational Physics*, **17**, J. Chang, Ed., Academic Press, 173-265.
- Bhaskaran, B., R. G. Jones, J. M. Murphy, and M. Noguer, 1996: Simulations of the Indian summer monsoon using a nested regional climate model: domain size experiments. *Clim. Dynam.*, **12**, 573-587.
- \_\_\_\_\_, A. Ramachandran, R. Jones, and W. Moufouma-Okia, 2012: Regional climate model applications on sub-regional scales over the Indian monsoon region: The role of domain size on downscaling uncertainty. *J. Geophys. Res.*, **117**, D10113, doi:10.1029/2012JD017956.
- Caesar, J., T. Janes, A. Lindsay, and B. Bhaskaran, 2015: Temperature and precipitation projections over Bangladesh and the upstream Ganges, Brahmaputra and Meghna systems. *Environ. Sci. Proc. Impacts*, **17**, 1047-1056, doi:10.1039/C4EM00650J.
- Cherchi, A., A. Alessandri, S. Masina, and A. Navarra, 2011: Effects of increased CO<sub>2</sub> levels on monsoon. *Clim. Dynam.*, **37**, 83-101, doi:10.1007/s00382-010-0801-7.
- Climate Profile of India Report, 2010: Met Monograph No. Environment Meteorology-01/2010. [Available online at <http://www.imd.gov.in/section/climate/StateLevelClimateChangeMonofinal.pdf>].
- Cullen, M. J. P., 1993: The unified forecast/climate model. *Meteorol. Mag.*, **122**, 81-94.
- Dash, S. K., M. S. Shekhar, and G. P. Singh, 2006: Simulation of Indian Summer monsoon circulation and rainfall using RegCM3. *Theor. Appl. Climatol.*, **86**, 161-172, doi:10.1007/s00704-006-0204-1.
- Davies, H. C., and R. E. Turner, 1977: Updating prediction models by dynamical relaxation: an examination of the technique. *Quart. J. Roy. Meteor. Soc.*, **103**, 225-245.
- Dimri, A. P., T. Yasunari, A. Wiltshire, P. Kumar, C. Mathison, J. Ridley, and D. Jacob, 2013: Application of regional climate models to the Indian winter monsoon over the western Himalayas. *Sci. Total Environ.*, **468**, S36-S47, doi:10.1016/j.scitotenv.2013.01.040.
- Dobler, A., and B. Ahrens, 2010: Analysis of the Indian summer monsoon system in the regional climate model COSMO-CLM. *J. Geophys. Res.*, **115**, D16101, doi:10.1029/2009JD013497.
- \_\_\_\_\_, and \_\_\_\_\_, 2011: Four climate change scenarios for the Indian summer monsoon by the regional climate model COSMO-CLM. *J. Geophys. Res.*, **116**, D24104, doi:10.1029/2011JD016329.
- Douville, H., 2005: Limitations of time-slice experiments for predicting regional climate change over South Asia. *Clim. Dynam.*, **24**, 373-391,

- doi:10.1007/s00382-004-0509-7.
- Edwards, J., and A. Slingo, 1996: Studies with a flexible new radiation code I: choosing a configuration for a large-scale model. *Quart. J. Roy. Meteor. Soc.*, **122**, 689-720.
- Ehret, U., E. Zehe, V. Wulfmeyer, K. Warrach-Sagi, and J. M. Liebert, 2012: HESS Opinions "Should we apply bias correction to global and regional climate model data?" *Hydrol. Earth Syst. Sci.*, **16**, 3391-3404, doi:10.5194/hessd-9-5355-2012.
- Gadgil, S., and S. Sajini, 1998: Monsoon precipitation in the AMIP runs. *Clim. Dynam.*, **14**, 659-689.
- Geethalakshmi, V., A. Lakshmanan, D. Rajalakshmi, R. Jagannathan, S. Gummidi, A. P. Ramaraj, K. G. Bhuvaneshwari, and R. Anbhazhagan, 2011: Climate change impact assessment and adaptation strategies to sustain rice production in Cauvery basin of Tamil Nadu. *Curr. Sci.*, **101**, 3-10.
- Gilbert, R. O., 1987: *Statistical methods for environmental pollution monitoring*. Van Nostrand Reinhold Co., 320 pp.
- Giorgi, F., and X. Bi, 2000: A study of internal variability of a regional climate model. *J. Geophys. Res.*, **105**, 29503-29521, doi:10.1029/2000JD900269.
- \_\_\_\_\_, and L. O. Mearns, 2002: Calculation of average, uncertainty range, and reliability of regional climate changes from AOGCM simulations via the reliability ensemble averaging (REA) method. *J. Climate*, **15**, 1141-1158, doi:http://dx.doi.org/10.1175/1520-0442(2002)015<1141:COAURA>2.0.CO;2.
- Goswami, B. N., V. Venugopal, D. Sengupta, M. S. Madhusoodanan, and P. K. Xavier, 2006: Increasing trend of extreme rain events over India in a warming environment. *Science*, **314**, 1442-1445, doi:10.1126/science.1132027.
- Hawkins, E., T. M. Osborne, C. K. Ho, and A. J. Challinor, 2012: Calibration and bias correction of climate projections for crop modelling: an idealised case study over Europe. *Agric. forest Meteorol.*, **170**, 19-31, doi:10.1016/j.agrformet.2012.04.007.
- Hingane, L. S., K. Rupa Kumar, and B. V. Ramana Murthy, 1985: Long-term trends of surface air temperature in India. *J. Climatol.*, **5**, 521-528, doi:10.1002/joc.3370050505.
- Ho, C. K., D. B. Stephenson, M. Collins, C. A. T. Ferro, and S. J. Brown, 2012: Calibration strategies: a source of additional uncertainty in climate change projections. *Bull. Amer. Meteor. Soc.*, **93**, 21-26, doi: http://dx.doi.org/10.1175/2011BAMS3110.1.
- Hong, S.-Y., and M. Kanamitsu, 2014: Dynamical Downscaling: Fundamental Issues from an NWP Point of View and Recommendations. *Asia-Pac. J. Atmos. Sci.*, **50**, 83-104, doi:10.1007/s13143-014-0029-2.
- IPCC, 2007: *Climate Change 2007, The physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 996 pp.
- Islam, M. N., M. Rafiuddin, A. U. Ahmed, and R. K. Kolli, 2007: Calibration of PRECIS in employing future scenarios in Bangladesh. *Int. J. Climatol.*, **28**, 617-628, doi:10.1002/joc.1559.
- Jacob, D., and Coauthors, 2007: An inter-comparison of regional climate models for Europe: design of the experiments and model performance. *Climatic Change*, **81**, 31-52, doi:10.1007/s10584-006-9213-4.
- Jones, R., M. Noguera, D. Hassell, D. Hudson, S. Wilson, G. Jenkins, and J. Mitchell, 2004: Generating high resolution climate change scenarios using PRECIS. [Available online at [http://www.metoffice.gov.uk/media/pdf/6/5/PRECIS\\_Handbook.pdf](http://www.metoffice.gov.uk/media/pdf/6/5/PRECIS_Handbook.pdf)].
- \_\_\_\_\_, A. Hartley, C. McSweeney, C. Mathison, and C. Buontempo, 2012: Deriving high resolution climate data for West Africa for the period 1950-2100. UNEP-WCMC Technical Report, 25 pp.
- Julien, C., M. Clemence, P. Benjamin, and R. Yves, 2011: Quantifying internal variability in a regional climate model: a case study for Southern Africa. *Clim. Dynam.*, **37**, 1335-1356, doi:10.1007/s00382-011-1021-5.
- Kang, I. S., K. Jin, B. Wang, K. M. Lau, J. Shukla, and V. Krishnamurthy, 2002: Intercomparison of the climatological variations of Asian summer monsoon precipitation simulated by 10 GCMs. *Clim. Dynam.*, **19**, 383-395, doi:10.1007/s00382-002-0245-9.
- Kershaw, R., and D. Gregory, 1997: Parametrization of momentum transport by convection. Part I. Theory and cloud modelling results. *Quart. J. Roy. Meteor. Soc.*, **123**, 1133-1151.
- Kotroni, V., S. Lykoudis, K. Lagouvardos, and D. Lalas, 2008: A fine resolution regional climate change experiment for the Eastern Mediterranean: Analysis of the present climate simulations. *Glob. Planet. Chang.*, **64**, 93-104, doi:10.1016/j.gloplacha.2008.10.003.
- Krishna Kumar, K., K. Kamala, B. Rajagoopalan, M. P. Hoerling, J. K. Eischeid, S. K. Patwardhan, G. Srinivasan, B. N. Goswami, and R. Nemani, 2010: The once and future pulse of Indian monsoonal climate. *Clim. Dynam.*, **36**, 2159-2170, doi:10.1007/s00382-010-0974-0.
- \_\_\_\_\_, S. K. Patwardhan, A. Kulkarni, K. Kamala, R. K. Koteswara, and R. Jones, 2011: Simulated projections for summer monsoon climate over India by a high-resolution regional climate model (PRECIS). *Curr. Sci.*, **101**, 3-10.
- Kripalani, R. H., J. H. Oh, A. Kulkarni, S. S. Sabade, and H. S. Chaudhari, 2007: South Asian summer monsoon precipitation variability: Coupled climate model simulations and Projections under IPCC AR4. *Theor. Appl. Climatol.*, **90**, 133-159, doi:10.1007/s00704-006-0282-0.
- Kulkarni, A., S. Patwardhan, K. Krishna Kumar, K. Ashok, and R. Krishnan, 2013: Projected climate change in the Hindu Kush-Himalayan region by using the high-resolution regional climate model PRECIS. *Mt. Res. Dev.*, **33**, 142-151, doi:http://dx.doi.org/10.1659/MRD-JOURNAL-D-11-00131.1.
- Kumar, P., and Coauthors, 2013: Downscaled climate change projections with uncertainty assessment over India using a high resolution multi-model approach. *Sci. Total Environ.*, **468**, S18-S30, doi:10.1016/j.scitotenv.2013.01.051.
- Lal, M., T. Z. Nozawa, S. Emori, H. Harasawa, K. Takahashi, M. Kimoto, A. Abe-Ouchi, T. Nakajima, T. Takemura, A. Numaguti, 2001: Future climate change: implication for Indian summer monsoon and its variability. *Curr. Sci.*, **81**, 1196-1207.
- Maraun, D., 2012: Nonstationarities of regional climate model biases in European seasonal mean temperature and precipitation sums. *Geophys. Res. Lett.*, **39**, L06706, doi:10.1029/2012GL051210.
- Marengo, J. A., R. Jones, L. M. Alves, and M. C. Valverde, 2009: Future change of temperature and precipitation extremes in South America as derived from the PRECIS regional climate modeling system. *Int. J. Climatol.*, **29**, 2241-2255, doi:10.1002/joc.1863.
- May, W., 2004: Variability and extremes of daily rainfall during the Indian summer monsoon in the period 1901-1989. *Glob. Planet. Chang.*, **44**, 83-105, doi:10.1016/j.gloplacha.2004.06.007.
- \_\_\_\_\_, 2011: The sensitivity of the Indian summer monsoon to a global warming of 2°C with respect to pre-industrial times. *Clim. Dynam.*, **37**, 1843-1868, doi:10.1007/s00382-010-0942-8.
- McGregor, J. L., 1997: Regional climate modeling. *Meteor. Atmos. Phys.*, **63**, 105-117.
- \_\_\_\_\_, 2013: Recent developments in variable-resolution global climate modelling. *Climatic Change*, **119**, doi:10.1007/s10584-013-0866-5.
- McSweeney, C. F., and G. J. Richard, 2010: Selecting members of the 'QUMP' perturbed- physics ensemble for use with PRECIS. Met office Hadley Centre. [Available online at <http://www.metoffice.gov.uk/media/pdf/e/3/SelectingCGMsToDownscale.pdf>].
- \_\_\_\_\_, G. J. Richard, and B. B. Ben, 2012: Selecting Ensemble Members to Provide Regional Climate Change Information. *J. Climate*, **25**, 7100-7121, doi:http://dx.doi.org/10.1175/JCLI-D-11-00526.1.
- Meehl, G. A., and Coauthors, 2007: Global Climate Projections. In *Climate*

- Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, 747-845.
- Mesinger, F., 1981: Horizontal Advection Schemes of a Staggered Grid - An Enstrophy and Energy-Conserving Model. *Mon. Wea. Rev.*, **109**, 467-478, doi:http://dx.doi.org/10.1175/1520-0493(1981)109<0467:HASOAS>2.0.CO;2.
- Met Office Report, 2012: Climate Change in Maharashtra. [Available online at [http://www.metoffice.gov.uk/media/pdf/c/a/GOM\\_brochure\\_for\\_web.pdf](http://www.metoffice.gov.uk/media/pdf/c/a/GOM_brochure_for_web.pdf)].
- Mohammad, A. R., and R. M. Mujibur, 2012: A Comprehensive Modeling Study on Regional Climate Model (RCM) Application-Regional Warming Projections in Monthly Resolutions under IPCC A1B Scenario. *Atmosphere*, **3**, 557-572, doi:10.3390/atmos3040557.
- Mukhopadhyay, P., S. Taraphdar, B. N. Goswami, and K. Krishna Kumar, 2010: Indian summer monsoon precipitation climatology in a high resolution regional climate model: Impact of convective parameterization on systematic biases. *Wea. Forecasting*, **25**, 369-387, doi: <http://dx.doi.org/10.1175/2009WAF2222320.1>.
- Murphy, J. M., and Coauthors, 2009: UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre. [Available online at <http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87893>].
- Nakićenović, N., and Coauthors, 2000: *Special report on emissions scenarios.* Cambridge University Press, 612 pp.
- Nazrul Islam, Md., 2009: Rainfall and Temperature Scenario for Bangladesh. *Open Atmos. Sci. J.*, **3**, 93-103.
- Önöz, B., and M. Bayazit, 2012: The Power of Statistical Tests for Trend Detection. *Turkish J. Eng. Environ. Sci.*, **27**, 247-251.
- Pant, G. B., and K. Rupa Kumar, 1997: *Climates of South Asia.* John Wiley & Sons, 344 pp.
- Parthasarathy, B., A. A. Munot, and D. R. Kothawale, 1994: All India monthly and seasonal rainfall series 1871-1993. *Theor. Appl. Climatol.*, **49**, 217-224.
- Prasanta Kumar Bal, A. Ramachandran, R. Geetha, B. Bhaskaran, P. Thirumurugan, J. Indumathi, and N. Jayanthi, 2016: Climate Change Projections for Tamil Nadu: Deriving High Resolution Climate Data by a Downscaling Approach Using PRECIS. *Theor. Appl. Climatol.*, **123**, 523-535, doi:10.1007/s00704-014-1367-9.
- Rajbhandari, R., A. B. Shrestha, A. Kulkarni, S. K. Patwardhan, and S. R. Bajracharya, 2014: Projected changes in climate over the Indus river basin using a high resolution regional climate model (PRECIS). *Clim. Dynam.*, **44**, 339-357, doi:10.1007/s00382-014-2183-8.
- Rajeevan, M., and J. Bhate, 2008: A high resolution daily gridded rainfall data set (1971-2005) for mesoscale meteorological studies. NCC Research Report, No 9, India Meteorological Department, 14 pp.
- \_\_\_\_\_, and R. S. Nanjundiah, 2009: Coupled model simulations of twentieth century climate of the Indian summer monsoon. *Current trends in science: platinum jubilee special*, N. Mukunda, Ed., Indian Academy of Sciences, 537-568.
- Revadekar, J. V., D. R. Kothawale, S. K. Patwardhan, G. B. Pant, and K. Rupa Kumar, 2012: About the observed and future changes in temperature extremes over India. *Nat. Hazards*, **60**, 1133-1155.
- Reichler, T., and J. Kim, 2008: How well do coupled models simulate today's climate? *Bull. Amer. Meteor. Soc.*, **89**, 303-311, doi:http://dx.doi.org/10.1175/BAMS-89-3-303.
- Rupa Kumar, K., and R. G. Ashrit, 2001: Regional aspects of global climatic change simulation: validation and assessment of climate response over Indian monsoon region to transient increase of greenhouse gases and sulphate aerosols. *Mausam*, **52**, 229-244.
- \_\_\_\_\_, A. K. Sahai, K. K. Kumar, S. K. Patwardhan, P. K. Mishra, J. V. Revadekar, K. Kamala, and G. B. Pant, 2006: High resolution climate changes scenarios for India for the 21st century. *Curr. Sci.*, **90**, 334-345.
- Simmons, A., S. Uppala, D. Dee, and S. Kobayashi, 2007: ERA-Interim: new ECMWF reanalysis products from 1989 onwards. *ECMWF Newsletter*, **110**, 25-35.
- Sperber, K. R., and T. N., Palmer, 1996: Interannual Tropical Rainfall Variability in General Circulation Model simulations associated with the atmospheric model intercomparison project. *J. Climate*, **9**, 2727-2750, doi:http://dx.doi.org/10.1175/1520-0442(1996)009<2727:ITRVIG>2.0.CO;2.
- Srivastava, A. K., M. Rajeevan, and S. R. Kshirsagar, 2008: Development of a high resolution daily gridded temperature data set (1969-2005) for the Indian region. *Atmos. Sci. Lett.*, **10**, 249-254.
- Teutschbein, C., and J. Seibert, 2013: Is bias correction of regional climate model (RCM) simulations possible for non-stationary conditions? *Hydrol. Earth Syst. Sci.*, **17**, 5061-5077, doi:10.5194/hess-17-5061-2013.
- Turner, A. G., 2011: Modeling monsoons: Understanding and predicting current and future behavior. *The Global Monsoon System: Research and Forecast*. 2nd ed., C.-P. Chang et al. Eds., World Scientific, 421-454.
- \_\_\_\_\_, and H. Annamalai, 2012: Climate change and the South Asian summer monsoon. *Nat. Climatic Change*, **2**, 587-595, doi:10.1038/nclimate1495.
- Uppala, S. M., and Coauthors, 2005: The ERA-40 Re-Analysis. *Quart. J. Roy. Meteor. Soc.*, **131**, 2961-3012, doi:10.1256/qj.04.176.
- Wang, B., I. S. Kang, and Y. J. Lee, 2004a: Ensemble simulations of Asian- Australian monsoon variability during 1997/1998 El Nino by 11 AGCMs. *J. Climate*, **17**, 803-818, doi:10.1029/2005GL022734.
- \_\_\_\_\_, Q. Ding, X. Fu, I. S. Kang, K. Jin, J. Shukla, and F. Doblas-Reyes, 2005: Fundamental challenge in simulation and prediction of summer monsoon rainfall. *Geophys. Res. Lett.*, **32**, L15711, doi:10.1029/2005GL022734.
- Wang, Y., L. R. Leung, J. L. McGregor, D.-K. Lee, W.-C. Wang, Y.-H. Ding, and F. Kimura, 2004b: Regional climate modeling: Progress, challenges, and prospects. *J. Meteor. Soc. Japan*, **82**, 1599-1628, doi:http://doi.org/10.2151/jmsj.82.1599.
- Zhang, Y., Y. L. Xu, W. J. Dong, L. J. Cao, and M. Sparrow, 2006: A future climate scenario of regional changes in extreme climate events over China using the PRECIS climate model. *Geophys. Res. Lett.*, **33**, L24702, doi:10.1029/2006GL027229.