Do CMIP5 models hint at a warmer and wetter India in the 21st century?

Rajib Maity, Ankit Aggarwal and Kironmala Chanda

ABSTRACT

This study diagnoses the spatio-temporal variation of three major hydroclimatic variables (temperature, precipitation and evaporation) estimated from four general circulation models participating in the Fifth Phase of the Coupled Model Intercomparision Project (CMIP5). Changes in climate regime are analyzed across India for the historical scenario (1850–2005) and for the RCP8.5 scenario (2006–2100). The study provides a relative assessment of projected changes in climatic pattern over different zones in India, broadly divided as southern, Eastern, Western, Central, North-Eastern and Himalayan regions. Monthly data for both the scenarios were obtained, and all the data were re-gridded to a common resolution. All the models show a stronger warming in the future as compared to the historical period. The North-Eastern, Northern and Himalayan regions are likely to be severely affected. Though inconsistencies have been observed among the models, the majority of them predict an increase in precipitation in future, with a major increment in southern cities. The Himalayan belt is expected to receive heavy rainfall in the summer season, with little change in the winter season. Most of the regions are not expected to experience change in evaporation in pre-monsoonal months, but substantial change is expected in some regions during monsoonal and post-monsoonal months.

Key words | climate change, CMIP5, evaporation, precipitation, RCP8.5, temperature

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INTRODUCTION

India exhibits a wide diversity of climates; the presence of the Himalayas in the north and the Thar Desert in the west play a key role in controlling the climate of India. The Himalayas act as a barrier to the cold winds from Central Asia, thereby making India warmer compared to its latitude, and the Thar Desert attracts the summer monsoon winds, which are responsible for the distinct monsoon season observed in India. However, over the past couple of centuries, anthropogenic activities such as deforestation and urbanization have led to changes in the earth's climate. Meteorological data over the past century suggest significant warming of the earth (Kumar *et al.* 2006); future projections of Asian monsoon are quite uncertain due to varied reasons (Turner & Slingo 2009; Lee & Wang 2012). According to the report by the Intergovernmental Panel on Climate Change (IPCC, 2014), climate change is already having substantial impacts 'on all the continents and across the oceans' and the worst is yet to come. As carbon emissions have accumulated over recent years, scientists are considering global warming as an alarming threat (Strauss 2013). Also, summer sea ice in the Arctic continues to dwindle and the movement of coastal Atlantic glaciers has resulted in an uncontrollable rise of the sea level (Proshutinsky *et al.* 2001; Khedun & Singh 2014). With the land–sea temperature difference projected to increase in coming years, the amount of water available as moisture in the atmosphere is going to increase further, leading to a more intense monsoon (Kitoh *et al.* 2013). According to the Indian Network for Climate Change Assessment (INCCA) report #2 (2010),

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increase in temperature, melting of ice and rise in sea level are some of the paradigm shifts that have been observed in recent years owing to the effects of global warming. The report concludes that India is expected to experience a 2 °C rise in temperature by 2030, along with increased annual precipitation with a lower frequency of rainy days. Such changes could have disastrous effects in a country like India, which is an agricultural economy (a climate sensitive sector).

Impacts of climate change have been studied by several researchers (Dhorde *et al.* 2009; Xu *et al.* 2009; Schewe *et al.* 2011; Chaturvedi *et al.* 2012). Kumar & Hingane (1988) have studied the past 86–112 years' data of long-term seasonal and annual temperatures for major Indian cities such as Calcutta (name changed to Kolkata), Bombay (name changed to Mumbai), Madras (name changed to Chennai), Pune, Bangalore (name changed to Bengaluru) and Delhi. The study reveals significant warming at some cities, namely Calcutta, Madras and Bombay, while a cooling trend is observed at Delhi. These significant changes could be due to the fact that these are major industrial cities of India, which are subjected to the continuous addition of gaseous pollutants and waste heat, which alter the components of radiation balance. On similar lines, Dhorde *et al.* (2009) studied the trends in annual and seasonal temperature using linear regression and the Mann-Kendall test, and emphasized the effect of urbanization, leading to a significant shift in temperature during the post-monsoon and winter seasons at four major Indian cities. Xu *et al.* (2009) raised specific concerns regarding cascading effects of climate change on water, biodiversity and livelihood in the Himalayas. The increased warming in the Himalayan region, resulting in the loss of ice and snow, would lead to huge effects on global sea level rise. In fact, estimates show a minimum average sea level rise of 80 cm by 2100 (Cruz *et al.* 2007) in comparison to the IPCC's conservative estimate of 40 cm. Such a phenomenon would have far-reaching effects such as the submergence of coastlines in the deltas of southern Asia and loss of agricultural land due to increased salinity.

The extent of change in the precipitation regime over India is still a matter of debate. There have been abnormalities or inconsistencies between different models in predicting the change in Indian monsoon rainfall. While Fu *et al.* (1999) show an increase in Indian monsoonal rainfall, Guhathakurta & Rajeevan (2008) show an overall decrease in annual rainfall in central and northern parts of India due to a decreased contribution from major monsoon months such as July and September. Yali *et al.* (2013) show the uncertainty in rainfall behavior, with an increase in mean rainfall for a short run period (1979–2005) and a decrease in rainfall for most parts for a long run period (1950–2005). With the advent of the Coupled Model Intercomparision Project 5 (CMIP5), which is one of the most coordinated multi-model change experiments ever attempted, some significant climate studies have been conducted in recent times. Levine *et al.* (2013) examined the relationship between Arabian Sea cold sea surface temperature (SST) bias and weak monsoon rainfall in CMIP5 models. The study is an attempt to unveil future projections by CMIP5 which suggest that Arabian Sea SST has the potential to weaken future monsoon rainfall in India by limiting flux acceleration through the non linearity of the Clausius–Clapeyron relationship. According to Ashfaq *et al.* (2009), based on the high resolution nested model, enhanced greenhouse gas forcing is the prime reason behind decreasing summer precipitation and the delay of monsoon onset in the South Asian regions. Further, the reduced runoff may severely affect agricultural production, water availability and hydroelectric power generation (Mall *et al.* 2006). The future evolution of Indian summer monsoon rainfall (ISMR) has been studied using 20 CMIP5 models (Menon *et al.* 2013) for both historical and RCP8.5 scenarios. Nineteen out of 20 models simulated a positive trend in mean monsoonal rainfall under RCP8.5. Also, 17 out of 20 models showed an increase in interannual variability. The study asserts that CMIP5 models are showing a northward shift in the monsoon circulation under global warming. It shows a strengthening of monsoon circulation in the northern parts of India and a weakening of circulation in the southern parts.

Evaporation is another important component of the hydrological cycle to significantly affect the water balance of the earth. Understanding the role of evaporation is very important for a country like India, which hugely depends on agriculture. Penman (1948) mentioned that evaporation can take place from three kinds of surfaces – wet bare soil, turf (grass or vegetation) and from open water. The last is called free surface evaporation, and is defined as water evaporated from an extensive open water surface per unit area under existing atmospheric conditions. Most of the studies refer to evaporation as free surface evaporation with respect to water availability to crops. For example, Chattopadhyay & Hulme (1997) investigated the historical variation of free surface evaporation and evapotranspiration for five decades, ranging from 1940 to 1990, for India. Three seasons, namely pre-monsoon, monsoon and post-monsoon, were analyzed in the study. The results demonstrate a decrease in evaporation for monsoon and pre-monsoon seasons in spite of an increase in temperature. A similar reduction in evaporation in the Volga river basin instead of an expected rise was observed earlier by Golubev *et al.* (2003). In the present CMIP5 model outputs, evaporation datasets are available at the surface and are defined as the flux (the unit being kg/m^{-2} s^{-1}) of water into the atmosphere due to conversion of both liquid and solid phases to vapour (from the underlying surface and vegetation). Thus evaporation from all sources is considered.

The Fifth Assessment Report of the IPCC made climate projections for the future using the newly developed Representative Concentration Pathways (RCPs) under CMIP5. The periodic assessment by the IPCC has relied heavily on general circulation model (GCM) simulations of future climate driven by various emission scenarios outlined by the RCPs. In this study, the CMIP5 model simulations of three climate variables: temperature, precipitation and evaporation, are utilized for an assessment of the changes in these variables at 48 locations across India for both historical and RCP8.5 scenarios. The study area and dataset are explained in the next section (Materials and Methods). The methodology adopted to regrid the variables and assess their changes is also discussed. The results and discussions section is presented afterwards. This section is divided into two subsections – Twentieth century climate change and Twenty-first century climate change (under the RCP8.5 scenario). Conclusions are presented at the end.

MATERIALS AND METHODS

The study is carried out over the whole of India, extending over 78 °E–98 °E and 8 °N–36 °N. Forty-eight grid intersections are found to fall within the Indian boundary (Figure 1). These grid locations are uniformly distributed throughout the Indian geographical region to account for spatial changes in climate all over India. The latitude and longitude of the 48 locations are given in Table 1.

In this study, the three major climate variables are considered, namely temperature, precipitation and evaporation. Four different climate models are selected from the CMIP5 project. These are CanESM2, CSIRO-Mk3.6.0, IPSL-CM5A-LR and IPSL-CM5A-MR. The different GCMs consider different forcing conditions. The second generation Canadian Earth System Model (CanESM2) combines the CanCM4 model and the terrestrial carbon cycle based on the Canadian Terrestrial Ecosystem Model (CTEM) (Chylek *et al.* 2011), which models the land-atmosphere carbon exchange. The 10 CTEM models are all primary terrestrial ecosystem processes including land use change based on historical changes in crop areas. The concentrations of greenhouse gases and solar variability are based on the CMIP5 recommendations. In addition, the effects of volcanic eruptions are included. The CanESM2 provides daily data at $2.813^\circ \times 2.79^\circ$ spatial resolution. CSIRO-Mk3.6.0 is developed by the Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence (QCCCE) (Rotstayn *et al.* 2012; Jeffrey *et al.* 2013). The horizontal resolution of this model is approximately $1.875^\circ \times 1.875^\circ$ with 18 vertical levels. As per Jeffrey *et al.* (2013), CSIRO-Mk3.6.0 includes a suite of historical experiments, and is suitable for detection and attribution studies, and a sufficient number (with respect to the CMIP5 minimum requirement) of the ensembles are available. The IPSL-CM5A-LR and IPSL-CM5A-MR are both provided by the Institut Pierre Simon Laplace (IPSL) Climate Modelling Centre, France. The IPSL CM5 corresponds to the last version of the IPSL model and is a full earth system model. Its primary strengths are that, in addition to the physical atmosphere-land-ocean-sea ice model, it also includes a representation of the carbon cycle, the stratospheric chemistry and the tropospheric chemistry with aerosols. The IPSL-CM5A is available at two standard resolutions – (i) LR stands for low resolution ($1.875^\circ \times 3.75^\circ$) while (ii) MR stands for mid-resolution ($1.25^\circ \times 2.5^\circ$).

The details of data availability and basic model information are shown in Table 2. The four models are chosen out of 24 GCMs based on the availability of data. We have

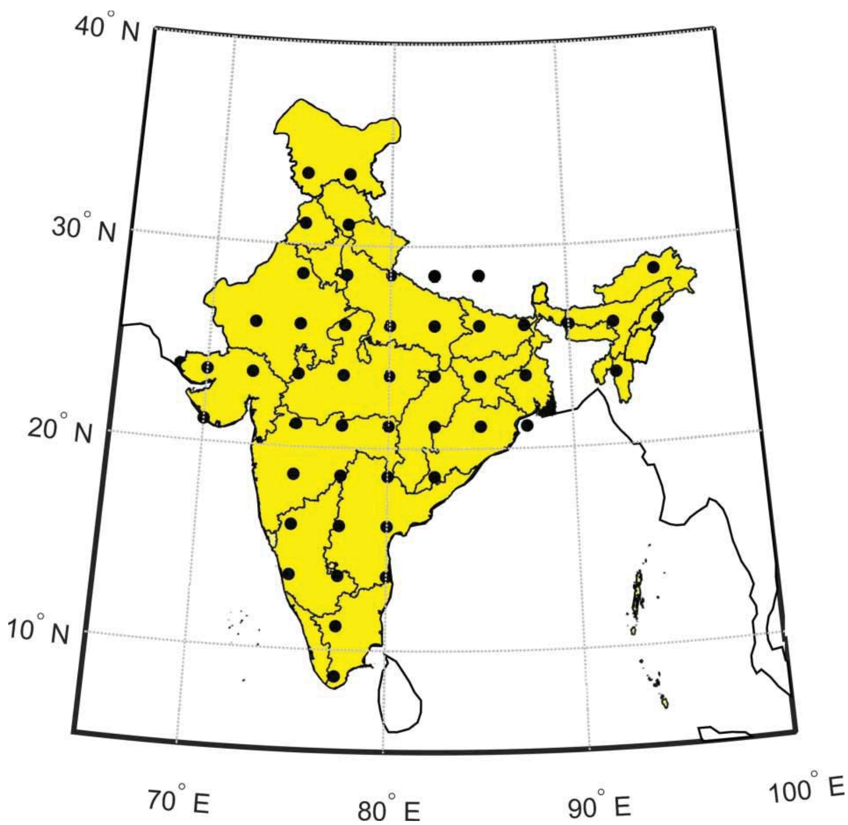

Figure 1 | Map of India with black dots denoting the 48 grid intersection points. Political boundary is indicative only.

analyzed four CMIP5 models with total ensembles of 22 simulations for historical experiments and four models with an ensemble size of 13 for the RCP8.5 experiments. The historical experiment simulations are focused on the 156-year period from January 1850 through December 2005. The historical experiments account for simulation with natural forcing (a mixture that might include solar and volcanic forcing) as well as anthropogenic forcing (a mixture that might include well-mixed greenhouse gases, aerosols, ozone, and land use changes). The RCP8.5 simulates a future projection that focused on a 95-year run from 2006 through 2100. This refers to a rising radiative forcing pathway leading to 8.5 W/m^2 in 2100. The RCP8.5 represents a situation where CO_2 equivalent concentrations are greater than 1,370 ppm, almost four times the present day atmospheric CO_2 concentration (Kumar *et al.* 2013). Similarly, RCP4.5 and RCP6.0 represent the pathways for which radiative forcing reaches 4.5 W/m^2 and 6 W/m^2, respectively, in 2100. RCP2.6 peaks in radiative forcing at 3 Wm^{-2} before 2100 and declines afterwards, reaching 2.6 Wm^{-2} in 2100 (Menon *et al.* 2013).

All the GCM models have different spatial resolutions. Thus, all of them are regridded or interpolated to a common resolution of 2.5° × 2.5°. Forty-eight grid intersections are found to fall within the Indian territory. For regridding GCM data, different functions in NCAR Command Language (NCL) are available at www.ncl.ucar.edu/Applications/regrid.shtml. Since interpolation of a scalar quantity from one Gaussian grid to another is required here, and the GCM gridded data are available for the whole globe, the function 'g2gsh_Wrap' (available at www.ncl.ucar.edu/Document/Functions/Contributed/g2gsh_Wrap.shtml) is found to be suitable and is utilized here.

After obtaining monthly regridded data for all the ensembles of all the models, the ensemble average is computed for each of the variables for each model at all grid intersections. For example, the regridded data are obtained for 48 grid points in India. For each grid point, monthly

Table 1 | Information about all the locations and their respective latitudes and longitudes are given. A total of 48 grid intersection points are covered in order to estimate the future climate of India

Location no.	Lon (°E)	Lat (°N)	Name of the state	Broad region
1	77.5	33.516	Jammu & Kashmir	N
2	77.5	31.034	Himachal Pradesh (near Shimla)	N
3	77.5	28.551	New Delhi	N
4	77.5	26.068	Madhya Pradesh (near Gwalior)	C
5	77.5	23.586	Madhya Pradesh (near Bhopal)	C
6	77.5	21.103	Maharashtra	W
7	77.5	18.62	Maharashtra	W
8	77.5	16.138	Karnataka (near Raichur)	S
9	77.5	13.655	Karnataka (near Bangalore)	S
10	77.5	11.172	Tamil Nadu	S
11	77.5	8.689	Tamil Nadu	S
12	75	33.516	Jammu& Kashmir	N
13	75	31.034	Punjab	N
14	75	28.551	Rajasthan	W
15	75	26.068	Rajasthan	W
16	75	23.586	Madhya Pradesh	C
17	75	21.103	Maharashtra	W
18	75	18.62	Maharashtra	W
19	75	16.138	Karnataka	S
20	75	13.655	Karnataka	S
21	85	28.551	Himalayas	H
22	85	26.068	Bihar (near Patna)	E
23	85	23.586	Jharkhand	E
24	85	21.103	Odisha	E
25	80	28.551	Himalayas	H
26	80	26.068	Uttar Pradesh (near Kanpur)	N
27	80	23.586	Madhya Pradesh (near Jabalapur)	C
28	80	21.103	Maharashtra (near Nagpur)	W
29	80	18.62	Andhra Pradesh	S
30	80	16.138	Andhra Pradesh	S
31	80	13.655	Andhra Pradesh	S
32	82.5	28.551	Himalayas	H
33	82.5	26.068	Uttar Pradesh	N
34	82.5	23.586	Chhattisgarh	C
35	82.5	21.103	Chhattisgarh (near Raipur)	C
36	82.5	18.62	Odisha	E
37	87.5	26.068	Bihar (near Purnia)	E
38	87.5	23.586	West Bengal (near Durgapur)	E
39	87.5	21.103	Odisha	E

(*continued*)

Table 1 | continued

Location no.	Lon (°E)	Lat (°N)	Name of the state	Broad region
40	90	26.068	Assam	NE
41	72.5	26.068	Rajasthan (near Jodhpur)	W
42	72.5	23.586	Gujarat (near Gandhinagar)	W
43	70	23.586	Gujarat (near Bhuj)	W
44	70	21.103	Gujarat	W
45	92.5	26.068	Assam	NE
46	92.5	23.586	Mizoram	NE
47	95	28.551	Arunachal Pradesh	NE
48	95	26.068	Nagaland	NE

N: northern region, S: southern region, W: western region, E: eastern region, C: central region, NE: north-eastern region, and H: Himalayas region.

Table 2 | Basic information on the selected CMIP5 models. Expansions of all the model acronyms are provided as a footnote of this table (available online at http://cmip-pcmdi.llnl.gov/cmip5/docs/CMIP5_modeling_groups.pdf)

S. no.	Model name	Country	Resolution (latitude × longitude)	Ensemble size	
				Historical	RCP8.5
1	CanESM2	Canada	$2.813^\circ \times 2.79^\circ$	5	5
2	CSIRO-MK3.6.0	Australia	$1.875^\circ \times 1.875^\circ$	9	3
3	IPSL –CM5A-LR	France	$1.875^\circ \times 3.75^\circ$	5	4
4	IPSL –CM5A-MR	France	$1.25^\circ \times 2.5^\circ$	3	1
Total ensembles				22	13

CanESM2: Canadian Centre for Climate Modelling and Analysis; CSIRO-MK3-6-0: Commonwealth Scientific and Industrial Research Organization; IPSL-CM5A-LR: Institut Pierre-Simon Laplace CM5A Low Resolution; IPSL-CM5A-MR: Institut Pierre-Simon Laplace CM5A Medium Resolution.

data are available for both the historical (1850–2005) and projected period for the RCP8.5 scenario (2006–2100). Since each model has multiple ensembles (different runs), data are averaged over a particular month across different ensembles to obtain a single value.

Furthermore, a best fit linear regression line is fitted to the monthwise time series of each variable in each scenario (historical and RCP8.5) and the slope (linear trend over time) is calculated. The slope of the line is further multiplied by the number of years in the respective scenario, which gives the change experienced by the variable over the study period for a particular month. For example, if the slope of the temperature time series is 0.03 °C/per year in January, then the change during 2006–2100 is computed as $0.03 \times 95 = 2.85$ °C. Such changes are computed for all the 12 months during this period. After computing such changes for each model and each location, the multi-model average is also computed in order to make final deductions. The multi-model average is taken, and necessary results are depicted using boxplots and maps.

RESULTS AND DISCUSSION

Before studying the change of the three variables (temperature, precipitation and evaporation) during the historical period (1850–2005) and future period (2006–2100) using GCM data, it is worthwhile carrying out a preliminary analysis on the association of the GCM datasets with observation during the historical period. For this purpose, daily precipitation and temperature data provided by the India Meteorological Department (IMD) at $1^\circ \times 1^\circ$ spatial resolution are used. The precipitation data are available for the historical period 1951–2003 and the temperature data are available for the period 1969–2005. These datasets are first converted to monthly scale and then their relationships with the corresponding CanESM datasets of the aforementioned periods are analysed. The scatter plots between IMD rainfall and CanESM rainfall are observed (figures not shown) and their correlation coefficients (r) are determined at various locations. The r value is found to be in the range of 0.05–0.81. In the case of temperature, the correlation coefficient between the IMD dataset and the CanESM dataset is found to be in the range of 0.81–0.98. In general, it is observed that the association of GCM rainfall with observations is not very good; however, the association of GCM temperature with observations is quite good. This observation is somewhat expected since most GCMs are known to have less accuracy in simulating precipitation. Thus, it may be noted that the future projections of temperature are possibly more reliable than that of precipitation. In the case of the latter, the GCM projections may give underestimated values based on their association during the historical period. Since the general tendency of GCM is to underestimate precipitation, when there is a projection of increasing precipitation, it may be accepted with more confidence.

TWENTIETH CENTURY CLIMATE CHANGE

Temperature

Across all models, locations and months, the range of temperature change in the pre-industrial period (1850–2005) varies from 1 to 3.62 °C. The maximum change (3.62 °C) is observed by CanESM2 in the month of April in the southern part of India. Large increments are also observed in the northern and eastern regions.

On observing the monthwise change in temperature (°C) in different models at different locations in the historical scenario, it is found that all the models, namely CanESM2, CSIRO, IPSL-MR and IPSL-LR, show a consistent increase in temperature at all locations over India. However, there is wide inconsistency among the models regarding the locations experiencing maximum change in temperature for a particular month. For instance, in January, according to CanESM2, maximum change is observed at location 9, i.e. Bangalore, whereas location 1, i.e. Jammu, witnesses a maximum change as per CSIRO. On the other hand, IPSL-LR and IPSL-MR indicate a maximum change at location 4, i.e. Gwalior and location 43, i.e. Bhuj, respectively. Similar observations are made for other months too. Again, the month showing the maximum change in temperature also varies across models. For instance, CanESM2 observes a maximum temperature change in the month of April, as 3.62 °C, whereas IPSL-MR observes it to be 2.76 °C and 3.51 °C in May and June, respectively.

Considering the multi-model average monthwise change in temperature (°C) in the historical scenario (1850–2005), it is observed that the changes are not consistent for different regions in India, rather, spatial variation is very prominent. Whereas some regions show an exceptional increase in temperature, others regions do not seem to follow the same trend. Large variations of 1–3 °C change are observed in the month of January in the Northern regions of the country such as Delhi, Jammu, Shimla, Punjab, Kanpur etc. In the month of March, more than five out of nine locations in Southern India have witnessed changes in temperature of more than 1.7 °C.

Precipitation

It is widely known that the Indian sub-continent is strongly affected by the south westerly monsoon winds in the months of June–September (Kharol *et al.* 2013) and the months June, July August and September (JJAS) are considered as the monsoon months. The model simulations brought forth a number of interesting features of the change in precipitation during these monsoon months. Figure 2 shows the change in precipitation for the JJAS months for all locations based on their multi-model average. Seven out of 48 locations showed an increase in precipitation over the past 156 years, the maximum being at location one.

Across all models, locations and months, the maximum change (2.76 mm/day) is observed in the Himalayas (location 21) by IPSL-LR in the month of August. However, the multi-model average is negative at this location (Figure 2). This points to the inconsistencies evident among the various model results. The monthwise change in precipitation averaged across all models for all the regions shows an interesting feature – all the months in all the locations show a decrease in precipitation. However, the North Eastern region has experienced an increase in precipitation in the months of May and February, with a maximum change of 0–0.9 mm/day.

Among the monsoonal months, the maximum decrease in precipitation is observed in the month of August. The regions – Southern, North Eastern, Himalayan and Western states – show a decrease of about 2 mm/day. Pre-monsoonal and post-monsoonal months show very little or no decrease in precipitation, the maximum value being 0.2 mm/day.

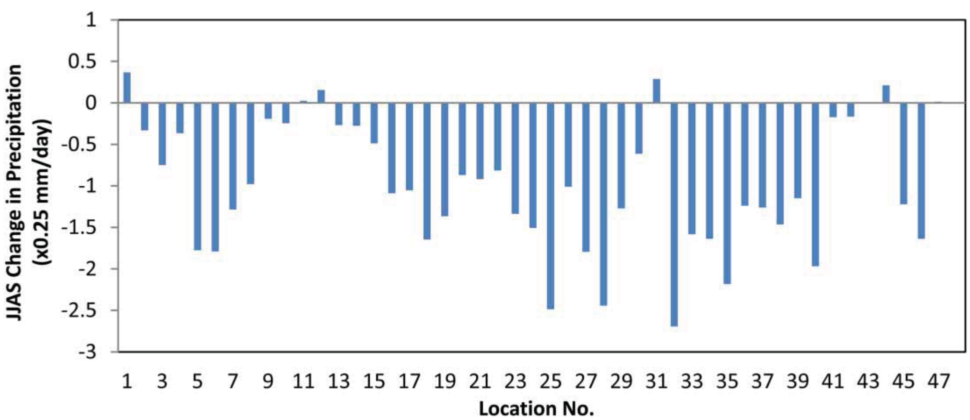

Figure 2 | Multi-model average change in JJAS precipitation at all locations for the historical scenario (1850–2005). Seven out of 48 locations showed an increase in precipitation during monsoonal months.

Evaporation

The monthwise change in evaporation (multi-model average) for all regions in India for the historical scenario (1850–2005) is studied. In general, all the months have seen little or no change in evaporation over this period. In the North Eastern region, a very small decrement of −0.03 mm/day is observed. Southern states such as Tamil Nadu and Kerala have observed relatively larger decrements in all the months. A decrease in evaporation was also observed in the months of June, July, August, September and October in Western, Central and North Eastern regions. In January, February and March, the maximum decrease in evaporation is noticed in the Western and Southern regions. Location 44 (Gandhinagar), location 43 (Bhuj) and location 20 (Karnataka) are the regions that are affected the most. Individually, among all the models, the maximum increase (0.354 mm/day) in evaporation in the 20th century is indicated by CanESM2 for the central region, i.e. Chhattisgarh. Again, the maximum decrease (–2.54 mm/day) in evaporation is observed in Tamil Nadu by the CSIRO.

TWENTY-FIRST CENTURY CLIMATE CHANGE (UNDER RCP8.5)

Temperature

The RCP8.5 combines assumptions about high population, which leads in the long-term to high energy demand and global greenhouse gas emissions in the absence of climate change policies (Riahi et al. 2011). The time period considered for change of temperature in RCP8.5 analysis is 95 years, i.e. from 2006 to 2100. Table 3 shows the region-wise maximum and minimum change in temperatures given by the multi-model average, while Figures 3 and 4 show the multi-model average change in temperature across India. The minimum and maximum changes, as given by the multi-model average, range from 4.7 to 10.7 °C. Major warming is observed in the Northern, Himalayan and North Eastern regions. The results are compared with the temperature projections obtained from Chaturvedi et al. (2012) which are based on CMIP5 models-projected temperature increase of 8 °C in India for the same period. Generally the northern part of the country is projected to experience higher warming compared to the Southern, Eastern, Western and Central parts. Areas in Rajasthan, Himalayas and North East such as Assam, Mizoram, and

Table 3 | Minimum and maximum temperature change (multi-model average) in different regions for RCP8.5 (2006–2100)

	Min (°C)	Max (°C)
North	4.7864	10.7431
East	3.9236	7.0968
West	4.2108	8.2368
South	4.0770	7.3055
Central	4.3916	7.7225
North East	5.1213	9.8716
Himalayas	4.7935	9.7395

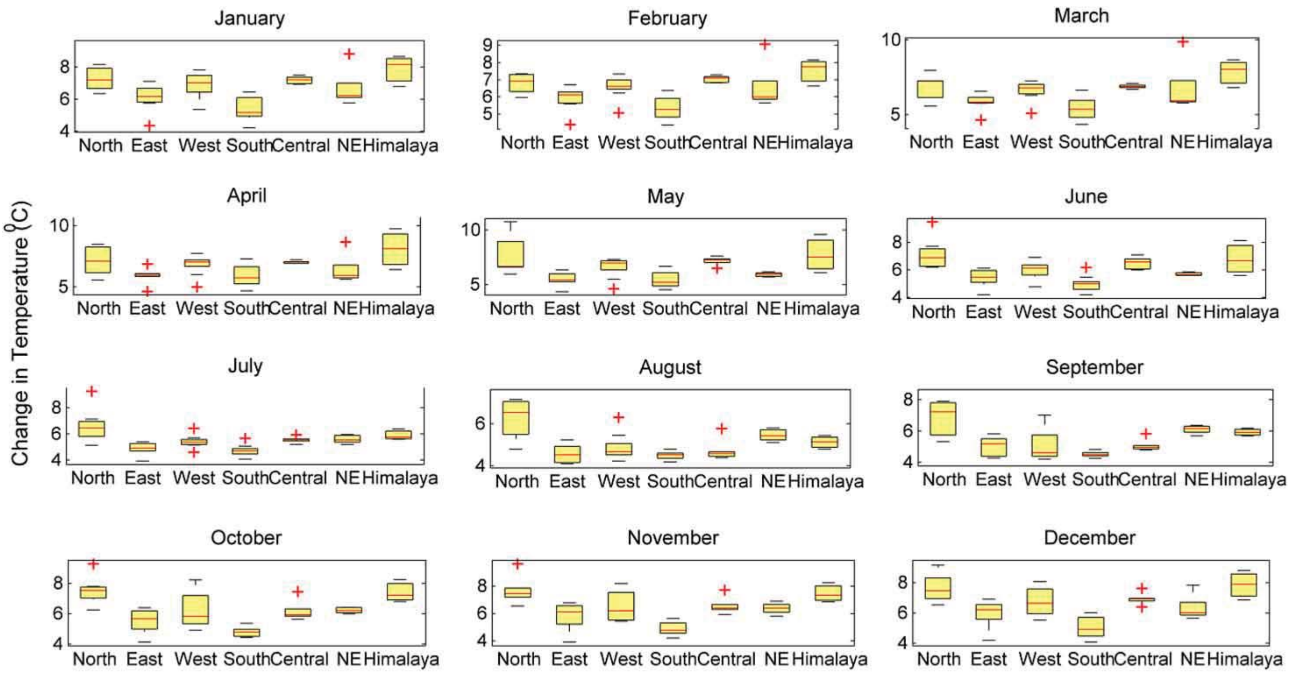

Figure 3 | Monthwise change in temperature (°C) for all regions in India for RCP8.5 scenario (2006–2100). The values observed by all four models are averaged and subsequently plotted using Box and whisker plots. The median values in each month depict average temperature change to be more than 5 °C. Northern, Himalayas and north eastern locations have relatively high median values compared to other regions.

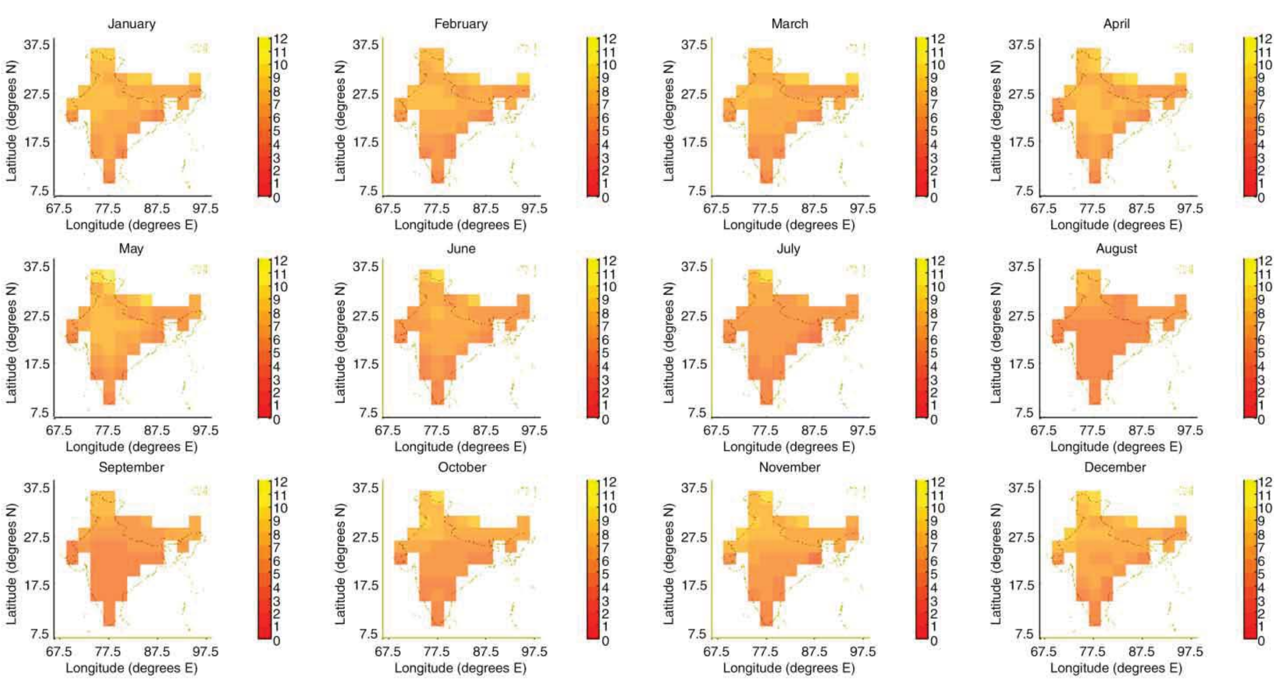

Figure 4 | Monthwise change in temperature (°C) in all regions of India for the RCP8.5 scenario (2006–2100). Northern locations such as Jammu could experience a major change in temperature across all months. The same variations could be observed in the Himalayas and Assam.

Arunachal Pradesh are particularly subject to higher warming, to the tune of 9.8 °C in 2100.

The temperature changes across all models, locations and months range from 1.3 to 13.6 °C, with the lowest being observed in the month of August at Nagpur (location 28) by the CSIRO model and the maximum change observed in the month of May at Jammu (location 1) by IPSL-CM5A-LR. Though there are inconsistencies among various models in quantifying the net change in temperature over the period of 2006–2100 in RCP8.5, all of them still predict an increase. The monthly variation in major regions of India such as Assam, Jammu, Himalayas and Rajasthan is presented in Figure 5 for all four different models. Three out of four models predict a steep increase in temperature in the month of May at Jammu, Assam and Himalayas. It seems that CSIRO is the only model that does not comply with most of the results presented by the rest of the models.

Precipitation

Across all models, locations and months, the maximum change in precipitation for the RCP8.5 scenario is observed in Assam in the month of August by CanESM2, the value being 14.67 mm/day. The multi-model average of precipitation in different regions is discussed below.

Figure 6 shows the multi-model average change in JJAS precipitation at all the locations. At each of the locations, the multi-model average suggests an increase in JJAS

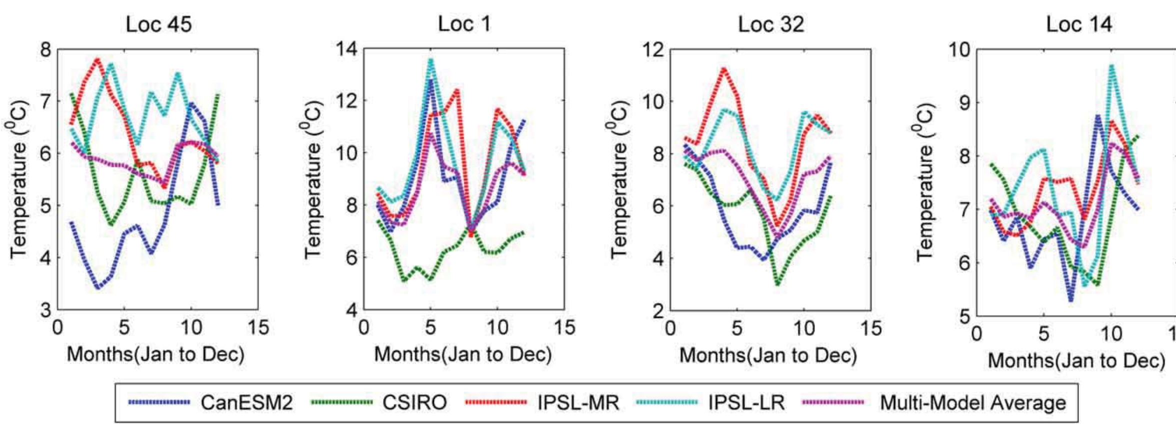

Figure 5 | Monthwise change in temperature (°C) for RCP8.5 (2006–2100) as predicted by different models. The graph is shown at locations that have experienced maximum change. The data are obtained by a best fit line fitted to the temperature change of the corresponding month over the study period. Four dotted lines represent the different models, whereas the fifth line represents the multi-model average.

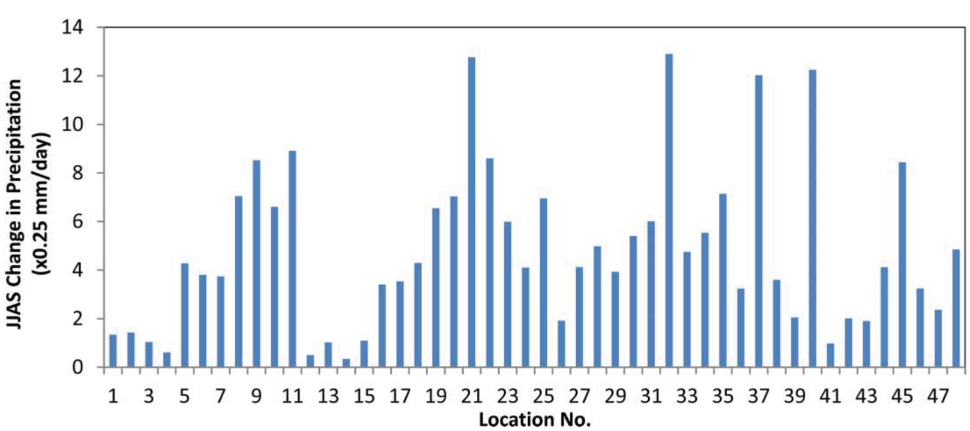

Figure 6 | Change in JJAS precipitation at all locations for RCP8.5 scenario (2006–2100).

precipitation, though some of the models individually suggest a decrease of the same. This increasing nature is contrary to the observation in the historical scenario.

Eastern and North Eastern regions are expected to be most affected during the months of May, June, July, August and September (Figures 7 and 8). The Western Ghats along the south-western coast of India could receive major rainfall in the month of August and September. Northern, Central and Western regions are expected to be affected to a much lesser extent.

Table 4 depicts the maximum and minimum values of the multi-model average precipitation change across different regions. North Eastern and Eastern regions (such as Assam, Mizoram, Nagaland, Odisha, Durgapur, Jharkhand, Patna etc.) are expected to receive a heavy rainfall change of 5.45 and 5.05 mm/day, respectively. On the other hand Northern, Western and Central regions are expected to experience much less change in rainfall. The Southern regions that are near to the coast of India like Tamil Nadu, the Western Ghats are likely to receive a considerable increase in precipitation along with the Himalayan belt (Figure 8).

Figure 9 shows that the four locations of Assam, Odisha, Himalayas and Tamil Nadu are expected to receive maximum rainfall in future scenarios. In general, the model variations comply with each other with respect to changes in precipitation for the future. All models agree on a heavy increment in rainfall during monsoonal and post-monsoonal months.

Evaporation

As reported earlier, evaporation was found to be decreasing for the historical scenario in the Western and Southern regions in the months of January, February and March. In the RCP8.5 scenario, evaporation shows an increasing trend in most of the regions in India (Figures 10–12). It is observed that Southern regions such as Tamil Nadu, Kerala etc. show the largest change in evaporation for most months, ranging from −0.08 mm/day in the month of April to 0.9 mm/day in the month of November. Central, western and Himalayan regions show a maximum change of 1.0 mm/day (September), 0.89 mm/day (September) and 0.88 mm/day (August), respectively. Northern regions such as Jammu, Delhi, and Haryana etc. are much less affected, along with some eastern and northeastern states. The evaporation change is observed to be around 0.6 mm/day in these regions. Considering the models individually, the maximum evaporation change (2.08 mm/day) is predicted by CSIRO at Bhopal (location 5).

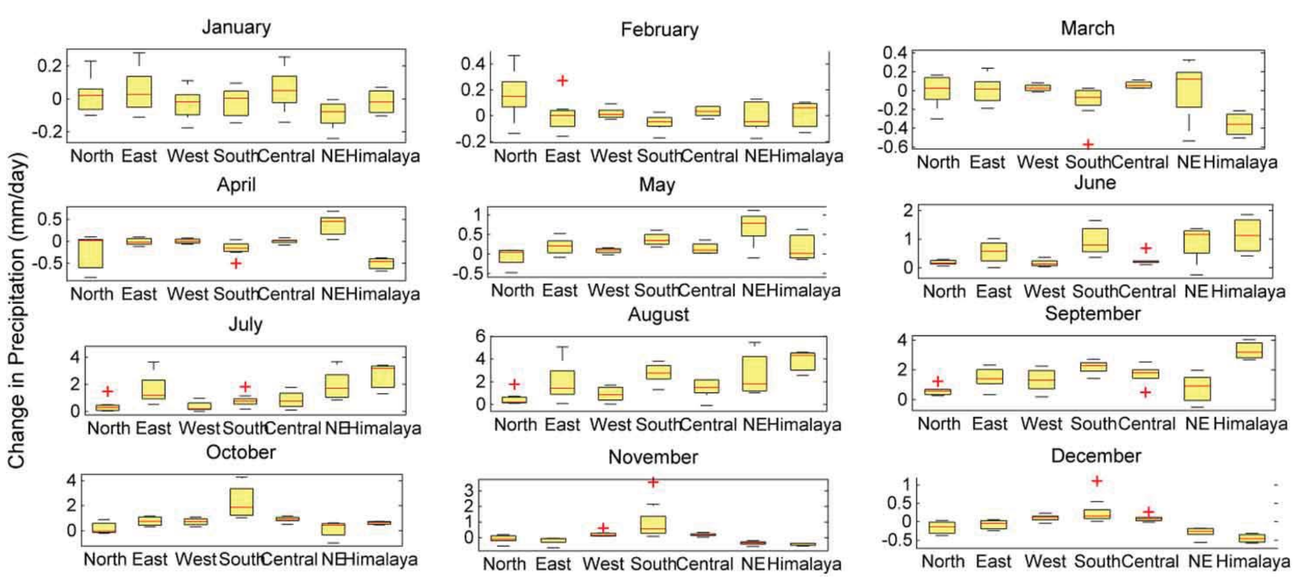

Figure 7 | Monthwise change in precipitation (mm/day) for all regions in India for RCP8.5 scenario (2006–2100). JJAS are the major monsoonal months in which north eastern and Himalayan locations experience maximum change in rainfall.

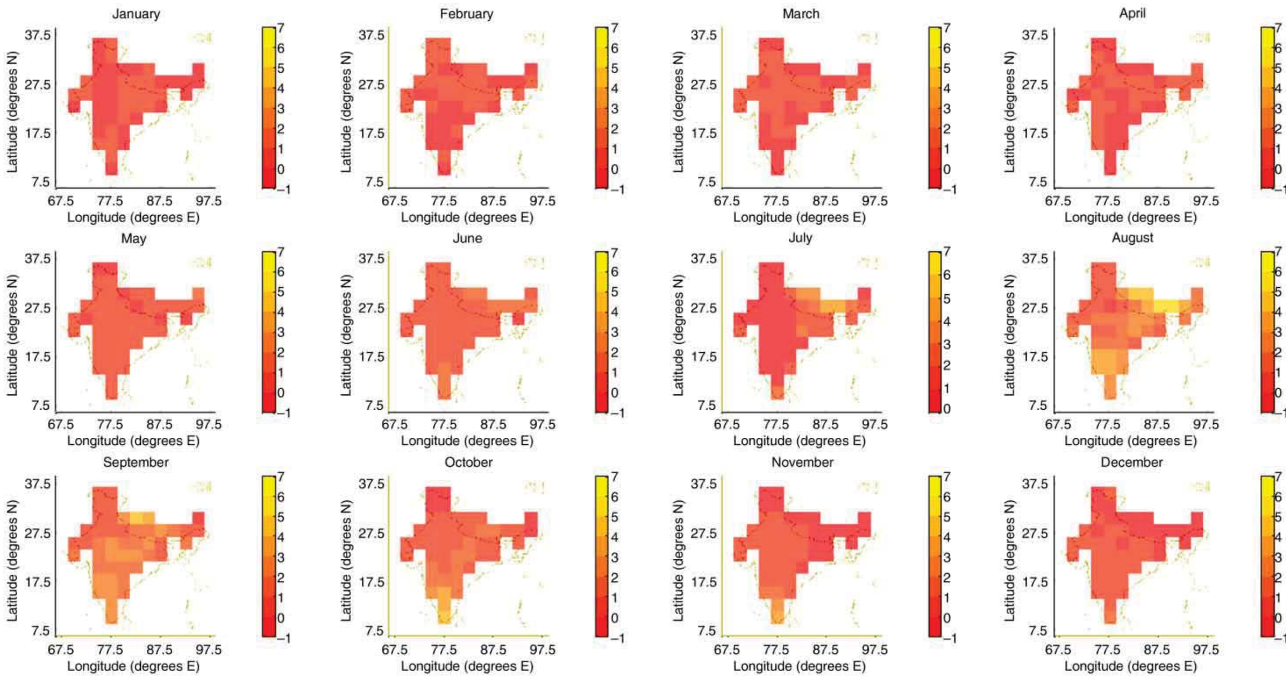

Figure 8 | Monthwise change in precipitation (mm/day) on all regions of India for the RCP8.5 scenario (2006–2100). Southern locations are bound to receive heavy rainfall in post-monsoonal seasons.

Table 4 | Minimum and maximum precipitation change (multi-model average) in different regions for RCP8.5 (2006–2100)

	Min (mm/day)	Max (mm/day)
North	−0.8219	1.7784
East	−0.6296	5.0516
West	−0.1752	2.2515
South	−0.5709	4.2672
Central	−0.1419	2.5205
North East	−0.9640	5.4499
Himalaya	−0.6755	4.5823

SUMMARY AND CONCLUDING REMARKS

Simulations from four GCM models, namely CanESM2, CSIRO, IPSL-CM5A-MR and IPSL-CM5A-LR are considered to assess monthwise changes in temperature, precipitation and evaporation across India for historical (1850–2005) and RCP8.5 (2006–2100) scenarios. Forty-eight grid intersection points are selected in such a way that all the regions, i.e. northern, western, eastern, north eastern, central, southern and the Himalayas, are well represented. The nature of changes in the climate variables for future scenarios do not seem to be very optimistic in relation to Global Warming. An increase in temperature is observed in all regions across India during the last century and also for future scenarios. All the major cities such as Delhi, Mumbai, Chennai etc. have shown a major increase in temperature. The effects of urbanization and increasing pollution in these regions could be the possible reasons for such observations. The high density of buildings in urban areas inhibits the transfer of heat to the higher atmosphere. This is one of the well known effects of urbanization, which develops when urban cooling rates are slower than rural ones. Apart from that, other possible reasons for this effect include heat emissions by buildings, air conditioning, transportation and industries. The temperature increase in the Northern, North-Eastern and Himalayan regions is a major concern. The Himalayan region, for example, holds the largest mass of ice outside the polar regions and is the source of the 10 largest rivers in Asia (Xu *et al.* 2009). A 10 °C increase in temperature in the Himalayas in RCP8.5 scenario could lead to serious problems for India as it

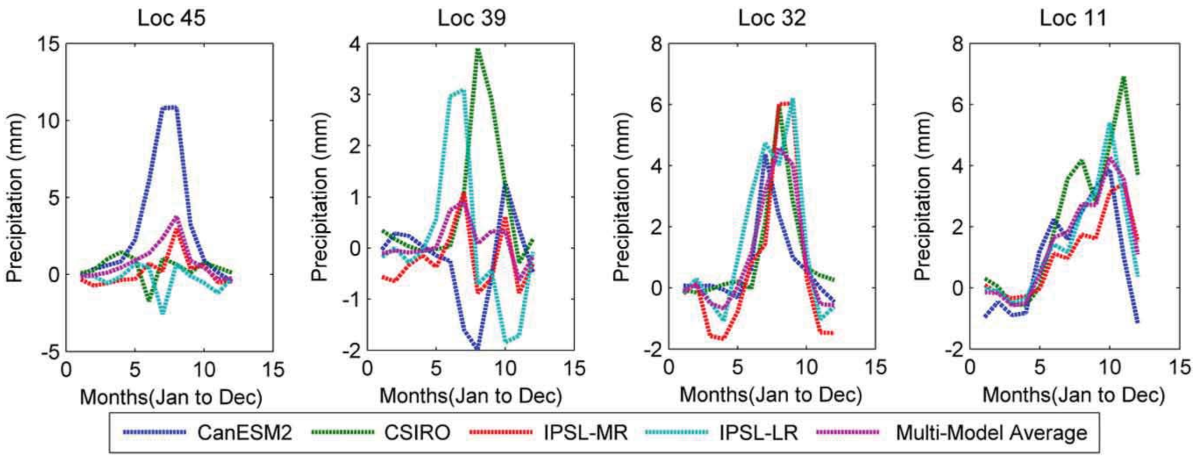

Figure 9 | Monthwise change in precipitation (mm/day) as predicted by different models for the RCP8.5 scenario (2006–2100). Assam (location 45), Odisha (Location 24), Himalayas (location 32) and Tamil Nadu (location 11) are the regions expected to receive the maximum change in rainfall. The Himalayas have achieved the highest coherency in terms of agreement among models on change in precipitation.

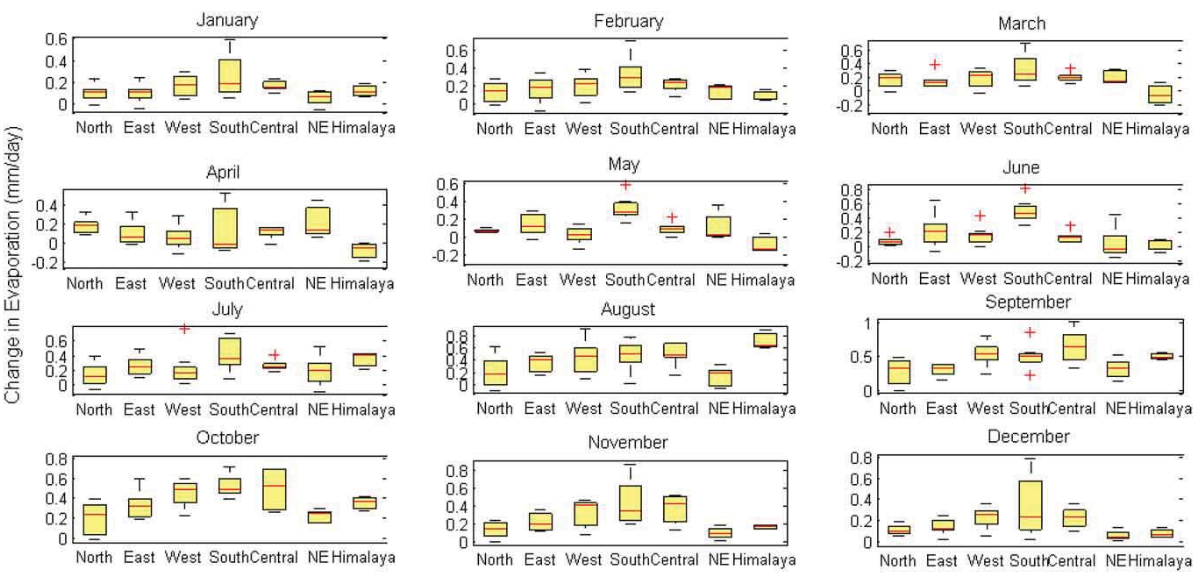

Figure 10 | Monthwise change in evaporation (mm/day) for all regions of India for the RCP8.5 scenario (2006–2100).

would immensely impact water availability, monsoonal behaviour and high-elevation ecosystems in that area.

This study also reviews the previous inconsistencies observed in precipitation for the historic period and provides a comparison with the future projected scenario. Outputs from CMIP5 models indicate a decrease in precipitation in the historical scenario, but an increase in precipitation for the RCP8.5 projection. In general, the ISMR is found to increase under future warming. These results are consistent with previous studies (Fu *et al.* 1999; Menon *et al.* 2013), which suggest a clear connection between the global temperature increase and Indian monsoonal rainfall. Kharol *et al.* (2013) cite pollution as one of the major factors for such an increment. Pollutants spewed from factories and vehicles lead to increased cloud formation, which often leads to heavy rainfall in some places. The major increment in precipitation is observed in southern cities like Bangalore, Hyderabad etc. These cities

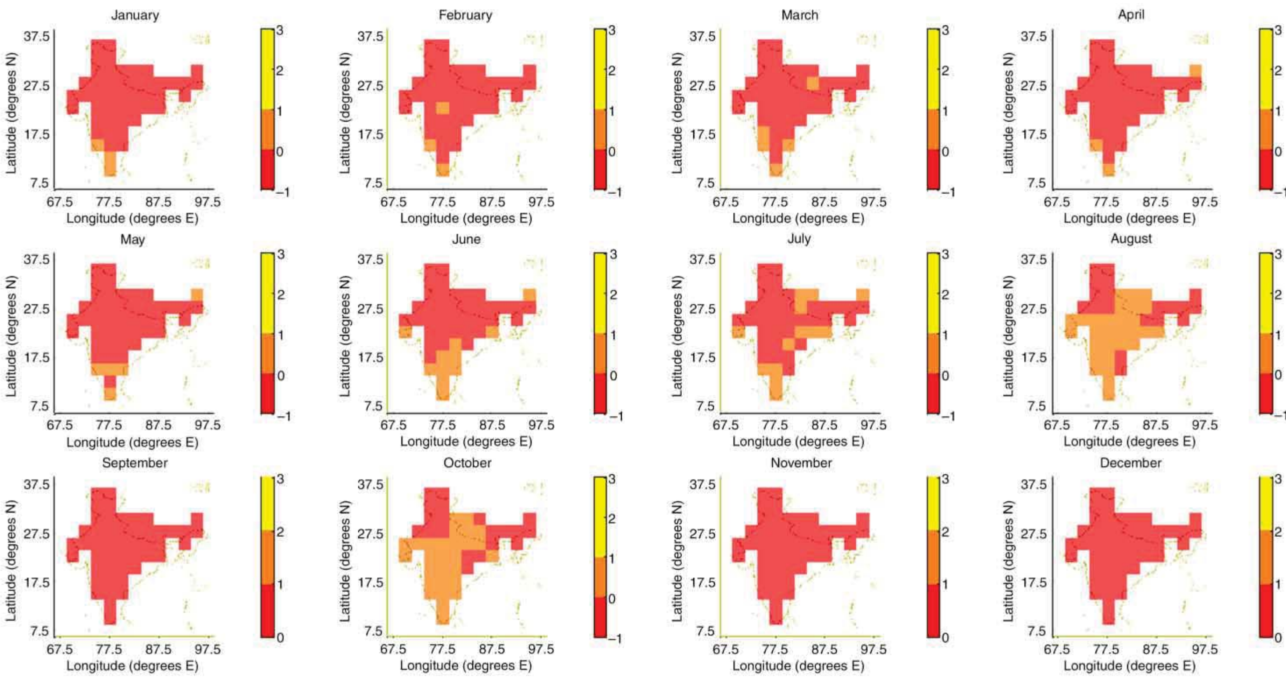

Figure 11 | Monthwise change in evaporation (mm/day) at all regions in India for RCP8.5 scenario (2006–2100).

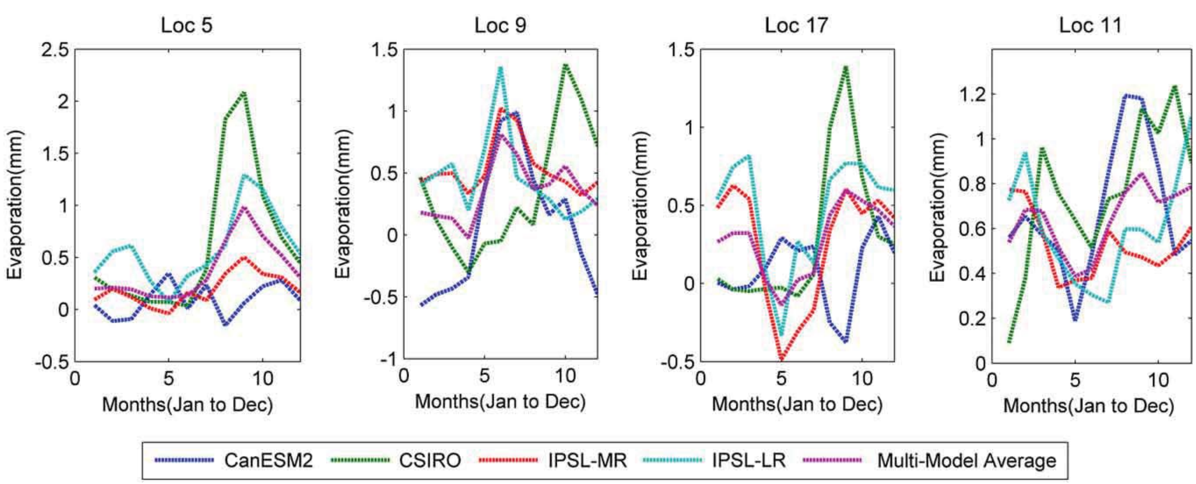

Figure 12 | Monthwise change in evaporation (mm/day) at various locations as predicted by different models for RCP8.5 scenario (2006–2100). Bhopal (location 5), Odisha (Location 9), Himalayas (location 17) and Tamil Nadu (location 11) are the regions expected to receive maximum change in evaporation.

have seen urban expansion and extensive changes in land use and land cover over the last 50 years, in addition to increased vegetation (Narayanan & Hanjagi 2009) and accelerated industrial activities, which could be the major cause for increased precipitation in these cities. Meanwhile, positive trends for winter monsoonal rainfall have been observed in the Western Ghats. In the Himalayan region, summer precipitation is projected to increase whilst very little change is projected for the winter months. The projected increase in the frequency and magnitude of high intensity rainfall events could affect infiltration and groundwater recharge, with further implications for water availability for people as well as vegetation (Sharma et al. 2009).

It is well established that emissions of carbon dioxide, aerosols and other pollutants have led to an increase in global temperatures over the last century; however, evaporation does not seem to follow the same trend. It may be expected that an increase in temperature would lead to an increase in precipitation and evaporation, and thus intensify the hydrological cycle. Contrarily, the present study shows a decrease in evaporation between 1850 and 2005 at most of the locations in India. The Northern and Himalayan regions have experienced relatively less change, about 0–0.2 mm/day compared to Southern, Western and Central regions where the change is 0–1.0 mm/day approximately. The result matches with the findings of Chattopadhyay & Hulme (1997), which state that temperature alone does not provide a satisfactory indication of changes in evaporation as is commonly presumed. For the RCP8.5 scenario, pre-monsoonal months do not show any significant change in evaporation at most of the locations, but the same cannot be said about monsoonal and post-monsoonal seasons. Southern, Central and Western regions are predicted to experience a change of about 0.9 mm/day during JJAS.

This study provides an insight into India's changing climate in the twentieth and twenty-first centuries. However, it needs to be appreciated that there are substantial disagreements in the outputs of the four models considered in this study. This is not unexpected, since the forces that drive climate change are rather complicated and uncertain. Hence, in addition to the adoption of sustainable policies globally, it is essential to devise climate resilient infrastructure and strategies for various sectors at the regional scale.

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