

# Multi-model climate change projections for India under representative concentration pathways

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**Climate projections for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) are made using the newly developed representative concentration pathways (RCPs) under the Coupled Model Inter-comparison Project 5 (CMIP5). This article provides multi-model and multi-scenario temperature and precipitation projections for India for the period 1860–2099 based on the new climate data. We find that CMIP5 ensemble mean climate is closer to observed climate than any individual model. The key findings of this study are: (i) under the business-as-usual (between RCP6.0 and RCP8.5) scenario, mean warming in India is likely to be in the range 1.7–2°C by 2030s and 3.3–4.8°C by 2080s relative to pre-industrial times; (ii) all-India precipitation under the business-as-usual scenario is projected to increase from 4% to 5% by 2030s and from 6% to 14% towards the end of the century (2080s) compared to the 1961–1990 baseline; (iii) while precipitation projections are generally less reliable than temperature projections, model agreement in precipitation projections increases from RCP2.6 to RCP8.5, and from short- to long-term projections, indicating that long-term precipitation projections are generally more robust than their short-term counterparts and (iv) there is a consistent positive trend in frequency of extreme precipitation days (e.g. >40 mm/day) for decades 2060s and beyond. These new climate projections should be used in future assessment of impact of climate change and adaptation planning. There is need to consider not just the mean climate projections, but also the more important extreme projections in impact studies and as well in adaptation planning.**

**Keywords:** Adaptation planning, climate change, temperature and rainfall projections, representative concentration pathways.

In 2000, the Intergovernmental Panel on Climate Change (IPCC) developed the global and regional emission path-

ways in its special report on emissions scenarios (SRES)<sup>1</sup>. It developed four families of emission pathways, namely A1, B1, A2 and B2 based on different socio-economic development assumptions. Global climate models under the Coupled Model Inter-comparison Project 3 (CMIP3) or better known as IPCC climate models (<http://www.ipcc-data.org/>) projected future climate change based on these emission pathways. The Fourth Assessment Report of IPCC used the SRES-based emission scenarios and climate projections from CMIP3 for characterizing future climate change and its impacts on society and ecosystems<sup>2,3</sup>.

In the past, climate projections for India have relied on the CMIP3 models. For instance, Krishnakumar *et al.*<sup>4</sup>, using CMIP3 multi-model data, provided projections of surface temperature and monsoon rainfall over India for the period 1901–2098. Global climate data from the Hadley Centre's Coupled Model (HadCM3) – one of the models among the CMIP3 experiment, have been also downscaled by a high-resolution regional climate model for India under the 'Providing Regional Climate for Impact Studies (PRECIS)' project<sup>5,6</sup>. Rupakumar *et al.*<sup>5</sup> simulated the regional climate of India by using PRECIS for the baseline (1961–1990) as well as long-term climatology (2071–2100) for the SRES scenarios A2 and B2. Krishnakumar *et al.*<sup>6</sup> also used PRECIS model to simulate the regional climatology of India for the period 1961–2098 for the SRES scenario A1B. Three simulations from a 17-member perturbed physics ensemble from HadCM3 for quantifying uncertainty in model predictions (QUMP) project were used to drive PRECIS in that study for three time periods, i.e. short (2020s), medium (2050s) and long term (2080s).

IPCC published the SRES scenarios in 2000 and the underlying economic and policy assumptions for these scenarios were fixed as early as by 1997 (ref. 7). SRES scenarios are nearly 15 years old. Now, the scientific community has developed a set of new-emission scenarios termed as representative concentration pathways (RCPs) (<http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=welcome>). In contrast to the

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**Table 1.** Description of representative concentration pathway (RCP) scenarios

RCP	Description	Developed by
RCP2.6	Its radiative forcing level first reaches a value around 3.1 W/m <sup>2</sup> mid-century, returning to 2.6 W/m <sup>2</sup> by 2100. Under this scenario greenhouse gas (GHG) emissions and emissions of air pollutants are reduced substantially over time.	IMAGE modelling team of The Netherlands Environmental Assessment Agency <sup>23</sup> .
RCP4.5	It is a stabilization scenario where total radiative forcing is stabilized before 2100 by employing a range of technologies and strategies for reducing GHG emissions.	MiniCAM modelling team at the Pacific Northwest National Laboratory's Joint Global Change Research Institute <sup>24</sup> .
RCP6.0	It is a stabilization scenario where total radiative forcing is stabilized after 2100 without overshoot by employing a range of technologies and strategies for reducing GHG emissions.	AIM modelling team at the National Institute for Environmental Studies, Japan <sup>25,26</sup> .
RCP8.5	It is characterized by increasing GHG emissions over time representative of scenarios in the literature leading to high GHG concentration levels.	MESSAGE modelling team and the IIASA Integrated Assessment Framework at the International Institute for Applied Systems Analysis (IIASA), Austria <sup>27</sup> .

SRES scenarios, RCPs represent pathways of radiative forcing, not detailed socio-economic narratives or scenarios. Central to the process is the concept that any single radiative forcing pathway can result from a diverse range of socio-economic and technological development scenarios. There are four RCP scenarios: RCP2.6, RCP4.5, RCP6.0 and RCP8.5. These scenarios are formulated such that they represent the full range of stabilization, mitigation and baseline emission scenarios available in the literature<sup>8</sup>. The naming convention reflects socio-economic pathways that reach a specific radiative forcing by 2100. For example, RCP8.5 leads to a radiative forcing of 8.5 Wm<sup>-2</sup> by 2100. The individual RCPs are briefly described in Table 1. New climate projections are being developed by different modelling groups based on these new RCP scenarios.

RCP-based climate projections are now available from a number of climate models under the CMIP5 experiment ([http://cmip-pcmdi.llnl.gov/cmip5/data\\_portal.html](http://cmip-pcmdi.llnl.gov/cmip5/data_portal.html)). CMIP5 includes a broader variety of experiments and application of more comprehensive models compared to CMIP3. CMIP5 models are generally of higher resolution compared to their CMIP3 counterparts<sup>9</sup>. Climate projections from all the modelling teams participating in the CMIP5 experiment are not yet available. However, it is useful to present a preliminary assessment based on the available models as of mid 2012, as the experience with CMIP3 indicates that general conclusions can be reached with a few models and uncertainties can be better quantified with the addition of more models at a later stage<sup>10</sup>. Climate projections for all the RCPs are available for only 18 models (as of June 2012). Model names, key features of their data outputs and research groups responsible for their development are described in Table 2.

In this study, we analyse projections for the two main variables: surface temperature (henceforth referred to as temperature) and precipitation for India, for each of the

CMIP5 models as listed in Table 2. For many models only one ensemble member, i.e. 'r1i1p1' is available (see Note 1), whereas for others more than one ensemble members are available; hence we have selected 'r1i1p1' ensemble member for all the models where possible and selected other ensemble members where this particular ensemble member is not available. The climatology data (historic as well as projected) are considered for the Indian region only, by masking out oceans and areas outside the geographical boundaries of India. Different CMIP5 model outputs are available on different spatial scales, as shown in Table 2; these outputs for both historic and climate projections are then regridded to a common spatial scale of 0.5 × 0.5 deg resolution using bilinear interpolation. Observed climate data from Climate Research Unit (CRU) is available at this resolution.

The study aims to: (i) Validate the new CMIP5-based climate projections (temperature and rainfall) for India by comparing the CMIP5-based model simulated climate for the period 1971–2000 with that of CRU-based observed climatology over the same period. (ii) Assess CMIP5-based short- (2030s representing climatology over 2021–2050), medium- (2060s representing climatology over 2046–2075) and long-term (2080s representing climatology over 2070–2099) climate change projections (temperature and precipitation) for India. (iii) Assess the projected change in frequency of extreme rainfall events over India based on CMIP5 projected climate change.

### Validation of CMIP5 models over India

Model-simulated baseline climatologies (individually as well as the model ensemble) are compared with the CRU observed climatologies<sup>11</sup> over the period 1971–2000 for both temperature and precipitation. The spatial pattern of annual temperature over the period 1971–2000, as

**Table 2.** List of climate models and ensemble outputs used in this study, their resolution and research groups responsible for their development

Model	Modelling centre (or group)	Resolution (lat.) – deg	Resolution (long.) – deg	Ensemble used/remark
CCSM4	National Center for Atmospheric Research, USA	0.942	1.250	R1i1p1
CSIRO-Mk3.6	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence, Australia	1.895	1.875	R1i1p1
GISS-E2-R	NASA Goddard Institute for Space Studies, USA	2.022	2.517	R1i1p1
HadGEM2-ES	Met Office, Hadley Centre, UK	1.250	1.875	R3i1p1 (r4i1p1 for pr in RCP8.5)
IPSL-CM5A-LR	Institut Pierre-Simon Laplace, France	1.895	3.750	r1i1p1 for RCP 4.5, 6.0, r3i1p1 for RCP2.6, 8.5
MIROC-ESM	Japan Agency for Marine–Earth Science and Technology, The University of Tokyo and National Institute for Environmental Studies	2.857	2.813	R1i1p1
MIROC-ESM-CHEM	Japan Agency for Marine–Earth Science and Technology, The University of Tokyo and National Institute for Environmental Studies	2.857	2.813	R1i1p1
MIROC5	The University of Tokyo, National Institute for Environmental Studies and Japan Agency for Marine–Earth Science and Technology	1.417	1.406	R1i1p1
MRI-CGCM3	Meteorological Research Institute, Japan	1.132	1.125	R1i1p1
NorESM1-M	Norwegian Climate Centre	1.895	2.500	R1i1p1
BCC-CSM1.1	Beijing Climate Center, China Meteorological Administration	2.812	2.812	R1i1p1
CESM1(CAM5)	Community Earth System Model Contributors	0.937	1.250	R1i1p1
FIO-ESM	The First Institute of Oceanography, SOA, China	2.812	2.812	R1i1p1
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory	2.000	2.500	R1i1p1
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory	2.000	2.500	R1i1p1
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory	2.000	2.500	R1i1p1
HadGEM2-AO	Met Office, Hadley Centre, UK	1.241	1.875	R1i1p1
NorESM1-ME	Norwegian Climate Centre	1.875	2.500	R1i1p1

simulated by the model ensemble is plotted along with the CRU-based observed annual temperature over India for the same period (Figure 1). CMIP5-based model ensemble simulates an all-India annual mean temperature of 22.9°C for the period 1971–2000, which is close to the observed annual mean temperature of 23.3°C for the same period. Apart from reasonably projecting the all-India mean annual temperature, CMIP5 ensemble is also able to broadly capture the observed spatial distribution patterns of temperature over India (Figure 1).

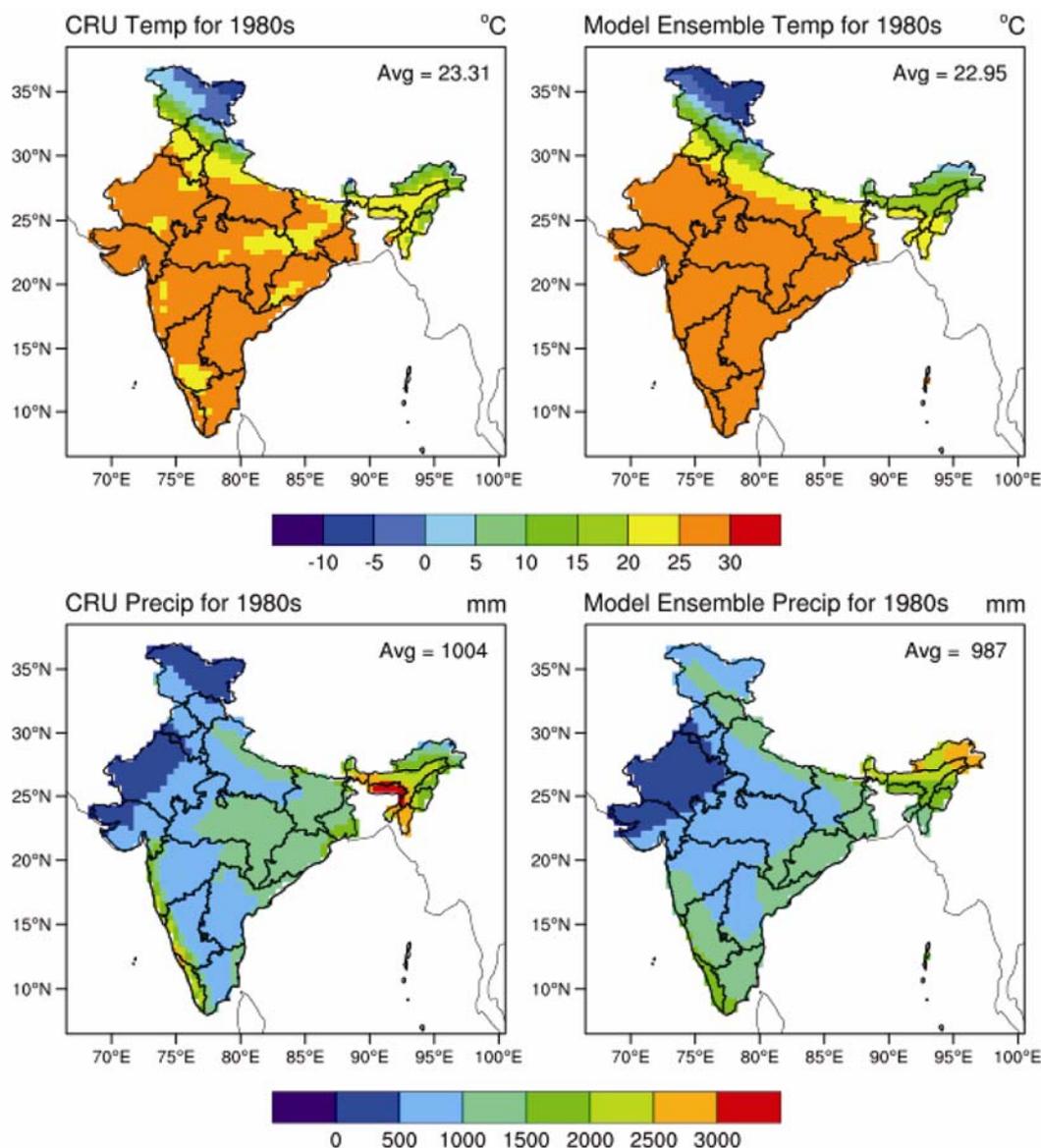
The spatial pattern of annual precipitation as simulated by the CMIP5 model ensemble is plotted along with the CRU-based observed annual precipitation over India for the period 1971–2000 (Figure 1). CMIP5 ensemble is able to simulate the broad spatial patterns of precipitation distribution in India reasonably well. For example, rainfall maxima are simulated in the Western Ghats and North East India and rainfall minima are simulated in western India.

Model performance is further studied for both the climate variables using Taylor diagrams<sup>12</sup>. Taylor diagrams are a convenient way of comparing different models using three related parameters: standard deviation, correlation with observed data and centred root mean square (RMS)

distance. Taylor diagrams are particularly convenient because they provide three metrics about the performance of a model at a single glance. As can be seen from Figure 2, the observed data lie at the point marked CRU. The green circles centred at the reference point represent loci of constant RMS distance and the circles centred at the origin represent loci of constant standard deviation. Correlation is represented as cosine of the angle from the X-axis. Models with as much variance as observation, largest correlation and least RMS error are considered best performers on the Taylor diagram.

Figure 2 suggests a good performance for the temperature variable by almost all the models. However, the model ensemble is closer to observations than any of the individual models. NorESM1-M, NorESM1-ME, CCSM4, FIO-ESM and MIROC5 are the individual models that are closer to the observations.

For the simulated precipitation, the models deviate significantly from observations. The RMS errors are large and the correlation is weak and ranges from 0.3 to 0.75. However, the model ensemble performs better than any individual model as it has the largest correlation and least RMS distance. GFDL-CM3 is the best-performing individual model, followed closely by several others.



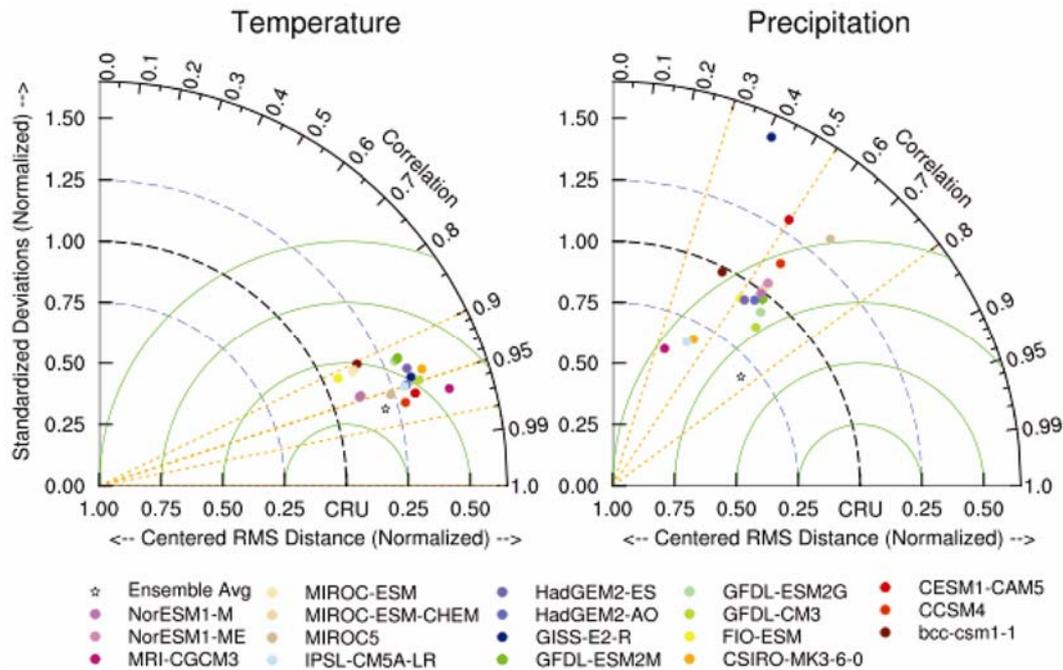
**Figure 1.** Comparison of ensemble mean temperature ( $^{\circ}\text{C}$ ) and precipitation (mm) as simulated by CMIP5 models for 1971–2000 (1980s) with observed temperature and precipitation distribution (Climate Research Unit; CRU) for the same period.

Results from the Taylor diagram suggest higher confidence for the temperature projections and relatively low confidence for the precipitation projections from CMIP5 models. These findings are well in line with the earlier findings involving the CMIP3 model experiments<sup>2</sup>.

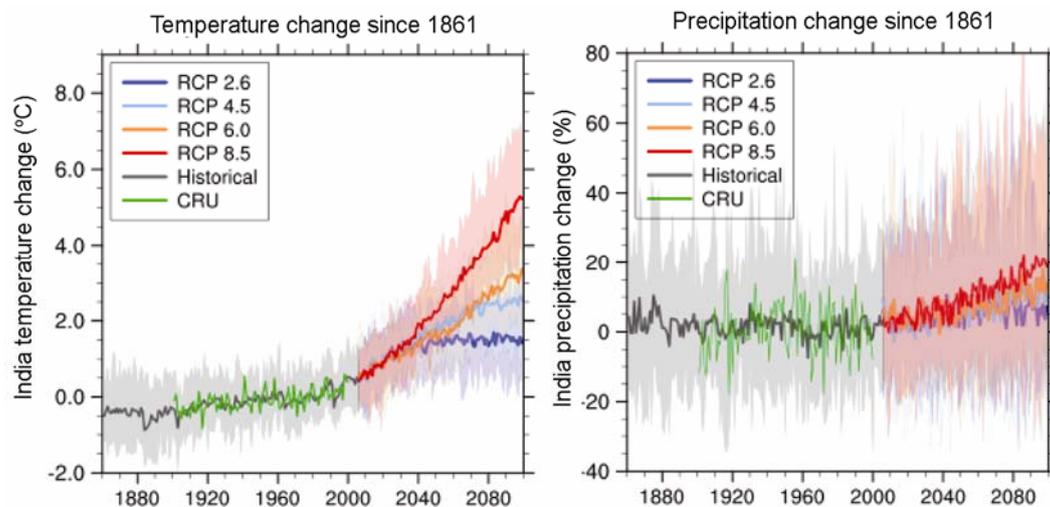
### Historical and projected climate change over India: a time-series view

The CMIP5 model-based historical and projected annual all-India mean temperature is shown in Figure 3. The CRU-based observed variability of temperature and precipitation falls well within the spread of the individual model simulations (grey cloud); further the observed

variability is well represented by the model ensemble. The range of temperature increase for all the RCPs by 2099 compared to the pre-industrial period (1880s, i.e. climatology over the period 1861–1900) is 1–8 $^{\circ}\text{C}$ , whereas this range comes down to 0.5–7 $^{\circ}\text{C}$  as the reference period shifts to 1961–1990. The latter is comparable with the temperature projections from Krishnakumar *et al.*<sup>4</sup> which are based on CMIP3 models-projected temperature increase of 2–6 $^{\circ}\text{C}$  for the same period. Figure 3 suggests that under RCP2.6 the ensemble mean temperature increases by approximately 2 $^{\circ}\text{C}$  over the period 1880s to 2070–2099, and 4.8 $^{\circ}\text{C}$  in RCP8.5. For RCP4.5 and RCP6.0, which represent the moderate scenarios, the projected increase in temperature ranges from 2.9 $^{\circ}\text{C}$  to 3.3 $^{\circ}\text{C}$ .



**Figure 2.** Taylor diagrams for temperature and precipitation, comparing CRU-based observations with the CMIP5 model and model ensemble simulations for India for the period 1971–2000.



**Figure 3.** CMIP5 model-based time series of temperature and precipitation anomalies (historical and projections) from 1861 to 2099 relative to the 1961–1990 baseline for the RCP scenarios. Shaded area represents the range of changes projected by the 18 models for each year. The model ensemble averages for each RCP are shown with thick lines. The observed temperature and precipitation trend from CRU is shown by the green line and the solid black line ‘historical’ refers to model ensemble values for historical simulations.

The CMIP5 model-based historical and projected annual all-India mean precipitation is also shown in Figure 3. All-India precipitation projections have larger uncertainties as evident from the large spread of the precipitation change projections in the figure, which ranges from  $-20\%$  to  $60\%$  towards the end of the century. Such a large uncertainty range in precipitation projections is also supported by Krishnakumar *et al.*<sup>4</sup> who used CMIP3 models. Our study based on CMIP5 models projects an

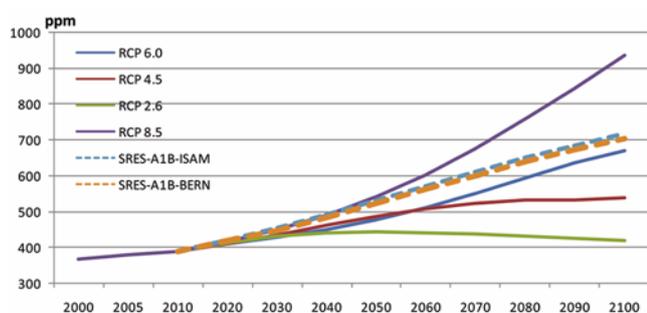
all-India ensemble-mean annual precipitation rise of 7%, 9.4%, 9.4% and 18.7% for RCP2.6, RCP4.5, RCP6.0 and RCP8.5 respectively, by 2099 compared to the 1961–1990 baseline (Figure 3).

As Krishnakumar *et al.*<sup>4</sup> do not provide climate projections for different SRES scenarios, their model ensemble mean is not comparable to our RCP-based projections. In Table 3, we compare RCP-based CMIP5 climate projections for India with available SRES-based projections in

**Table 3.** All-India average annual temperature and rainfall change projections for 2080s\* relative to the 1961–1990 baseline

	Study	Simulation	Projected change in temperature (°C) and precipitation (%) under different climate change scenarios						
			A2	B2	A1B	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Temperature (°C)	Rupakumar <i>et al.</i> <sup>5</sup>	PRECIS	4.1	2.9					
	Krishnakumar <i>et al.</i> <sup>6</sup>	Q0			4.1				
		Q1			3.5				
		Q14			4.3				
	This study	19 CMIP3 model ensemble			3.19				
This study	18 CMIP5 model ensemble				1.5	2.4	2.8	4.3	
Precipitation (%)	Rupakumar <i>et al.</i> <sup>5</sup>	PRECIS	23	18					
	Krishnakumar <i>et al.</i> <sup>6</sup>	Q0			15				
		Q1			13				
		Q14			12				
	This study	18 CMIP5 model ensemble				6	10	9	14

\*All the projections are for the 30 year average of 2071–2100 relative to the 1961–1990 baseline. However, CMIP3 projections are for the period 2067–2097 and CMIP5 projections are for the period 2070–2099.



**Figure 4.** Atmospheric CO<sub>2</sub> concentration under different RCP scenarios and SRES A1B scenario. RCP scenarios obtained from: <http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=compare> (last accessed on 5 April 2012) and SRES A1B scenario obtained from: <http://www.ipcc-data.org/ancillary/tar-bern.txt> and <http://www.ipcc-data.org/ancillary/tar-isam.txt> (last accessed on 5 April 2012).

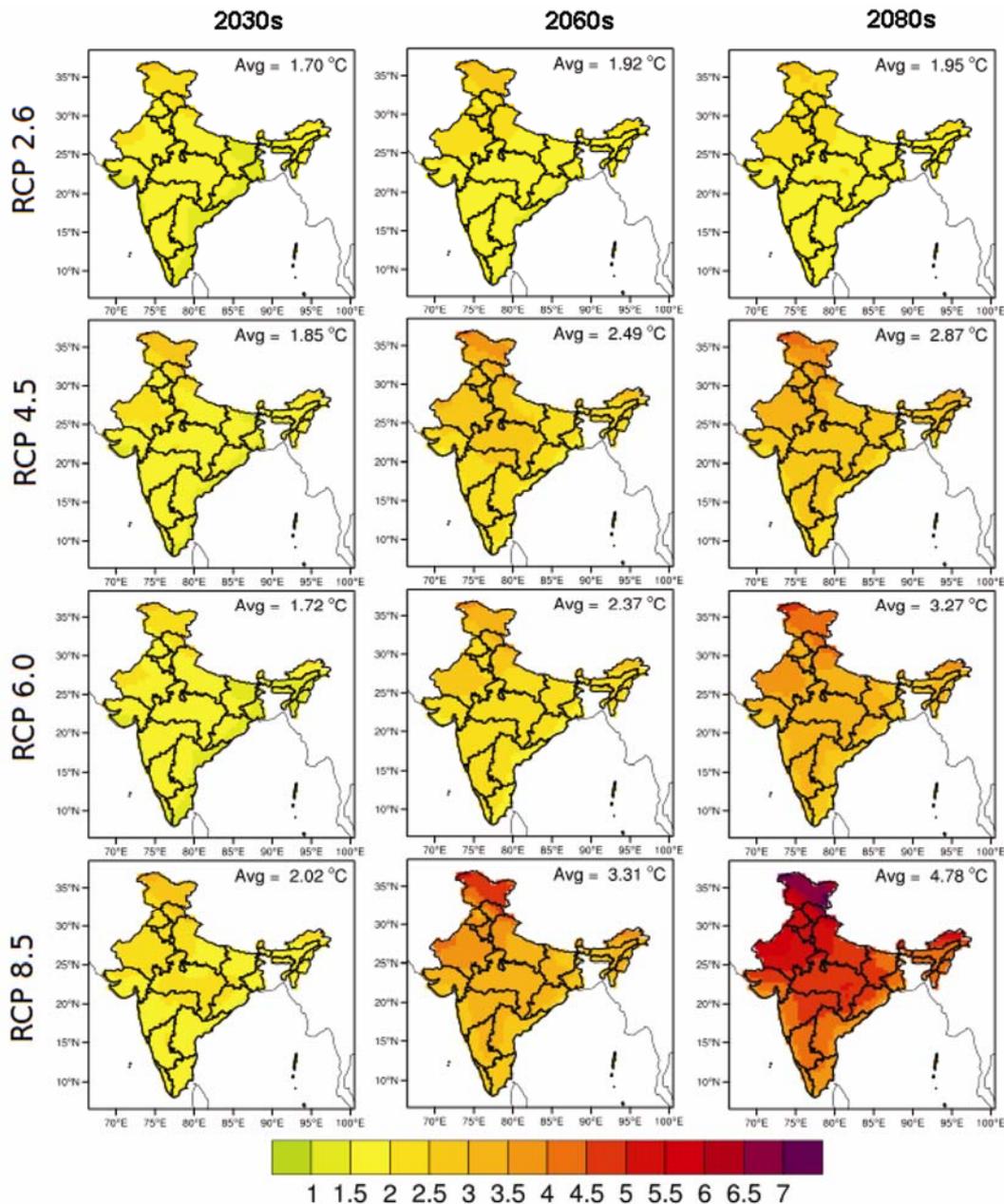
the literature. Rupakumar *et al.*<sup>5</sup> project a temperature rise of 2.9°C and 4.1°C for India under the B2 and A2 scenarios of SRES respectively, in 2080s relative to 1970s. Krishnakumar *et al.*<sup>6</sup> projected a warming of 3.5–4.3°C over the same period for the A1B scenario. A1B scenario of SRES is generally considered close to the business as usual emission scenario<sup>13</sup>. The CMIP5-based model ensemble projects a warming of 2.8°C and 4.3°C under the RCP6.0 and RCP8.5 scenarios respectively, for 2080s compared to the 1970s baseline. In terms of atmospheric CO<sub>2</sub> concentration build-up, the A1B scenario is closer to RCP8.5 until 2050, but then diverges and is closer to RCP6.0 between 2050 and 2100 (Figure 4). Climate change projections made by Rupakumar *et al.*<sup>5</sup> and Krishnakumar *et al.*<sup>6</sup> for India are based on a single climate model HadRM3 for specific scenarios, whereas our analysis is based on multiple model outputs for multiple scenarios. To facilitate a more reasonable comparison to previous estimates, we calculated the all-India warming based on an ensemble of 19 general circulation models (GCMs) from the CMIP3 experiment for the SRES A1B

scenario. These models are: CGMR, CGHR, CNCM3, CSMK3, MPEH5, ECHOG, FGOALS, GFCM21, GIAOM, GIEH, INCM3, IPCM4, MIHR, MIMR, MRCGCM, NCPDM, NCCCSM, HADCM3, HADGEM. The CMIP3-based model ensemble mean projects a warming of 3.19°C under the A1B scenario for 2080s compared to the 1970s baseline. Table 3 suggests that CMIP5-based new climate projection estimates are generally in agreement with earlier projections available in the literature.

The CMIP5 ensemble-based precipitation projections too are generally in line with the earlier estimates. PRECIS-based simulations (Table 3) project an increase of 12–23% in all-India precipitation by 2080s relative to 1970s, while CMIP5-based ensemble projects an all-India precipitation increase of 6–14% under different RCP scenarios over the same period.

### CMIP5 model ensemble-based temperature change projections for short, medium and long-term scenarios

Figure 5 shows the CMIP5 model ensemble-based annual temperature change (°C) projected for 2030s, 2060s and 2080s relative to the pre-industrial baseline (1880s) for the four RCP scenarios. All-India annual mean temperature increases by 1.7–2.02°C by 2030s under different RCP scenarios and by about 2–4.8°C by 2080s, relative to the pre-industrial base. Figure 5 projects a consistent warming trend over the country in short-, mid- as well as long-term scenarios. As expected in each of the three time slices RCP2.6 generally experiences the least warming, whereas RCP8.5 is associated with the highest warming, with RCP4.5 and RCP6.0 representing the moderate warming scenarios. Generally northern part of the country is projected to experience higher warming compared



**Figure 5.** CMIP5 model ensemble mean temperature change ( $^{\circ}\text{C}$ ) projected for 2030s (2021–2050), 2060s (2046–2075) and 2080s (2070–2099) relative to the pre-industrial period (1880s, i.e. over 1861–1900).

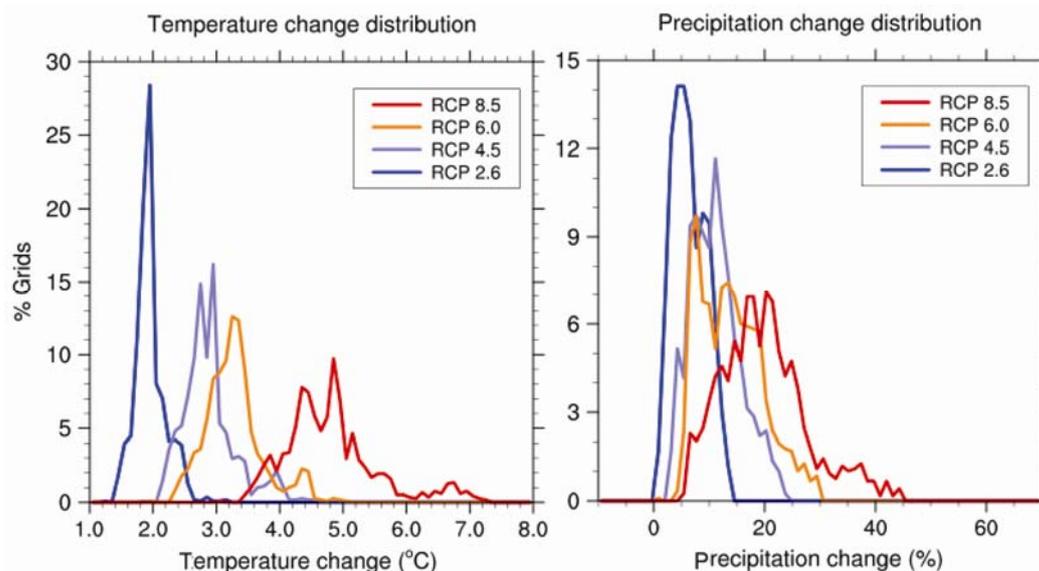
to the southern counterpart. Areas in the Himalayas and Kashmir are particularly subject to large warming to the tune of  $8^{\circ}\text{C}$  in RCP8.5 by 2099.

Figure 6 shows the India-level grid-wise distribution of projected temperature change under different RCP scenarios by 2080s. It shows that in RCP2.6 majority of the regions will experience a temperature rise of  $2^{\circ}\text{C}$  with the minimum temperature rise of about  $1.4^{\circ}\text{C}$  and a maximum of about  $2.8^{\circ}\text{C}$ . The minimum temperature rise increases to  $2^{\circ}\text{C}$  in RCP4.5 and  $3.4^{\circ}\text{C}$  in RCP8.5. Temperature increase in RCP6.0 is similar but larger than RCP4.5. Figure 6 also suggests that the variance (width

of the distribution) of the temperature rise increases rapidly from the RCP2.6 to RCP8.5.

### CMIP5 model ensemble-based precipitation change projections for short, medium and long-term scenarios

Figure 7 shows the CMIP5 model ensemble-based annual precipitation change (%) projected by 2030s, 2060s and 2080s respectively, compared to the pre-industrial baseline (1880s) for the four RCP scenarios. All-India annual



**Figure 6.** CMIP5 model ensemble-based grid-wise distribution of temperature and precipitation change under different RCP scenarios for India for 2080s (2070–2099) relative to pre-industrial period (1880s, i.e. over 1861–1900).

precipitation increases by 1.2–2.4% by 2030s under different RCP scenarios and by 3.5–11.3% by 2080s, relative to the pre-industrial base. Precipitation is projected to increase almost all over India except for a few regions in short-term projections (2030s). As noted in the temperature trends in each of the three time slices, RCP2.6 experiences the least increase in precipitation, whereas RCP8.5 experiences the highest precipitation increase, and the precipitation changes are larger for each subsequent period (i.e. short, mid and long term).

Figure 6 shows the country-level grid-wise distribution of precipitation changes under different RCP scenarios by 2080s from the CMIP5 model ensemble. Figure 6 shows that overall annual precipitation is projected to change from 0% to 45% under different scenarios of climate change by 2080s. RCP2.6 experiences the least change in precipitation, with the projected precipitation change varying from 0% to 15% and RCP8.5 is associated with the largest changes in precipitation, with the projected precipitation changes varying from 5% to 45%. As noted for the temperature projections, the variance (width of the distribution) in rainfall projections also increases from RCP2.6 to RCP8.5.

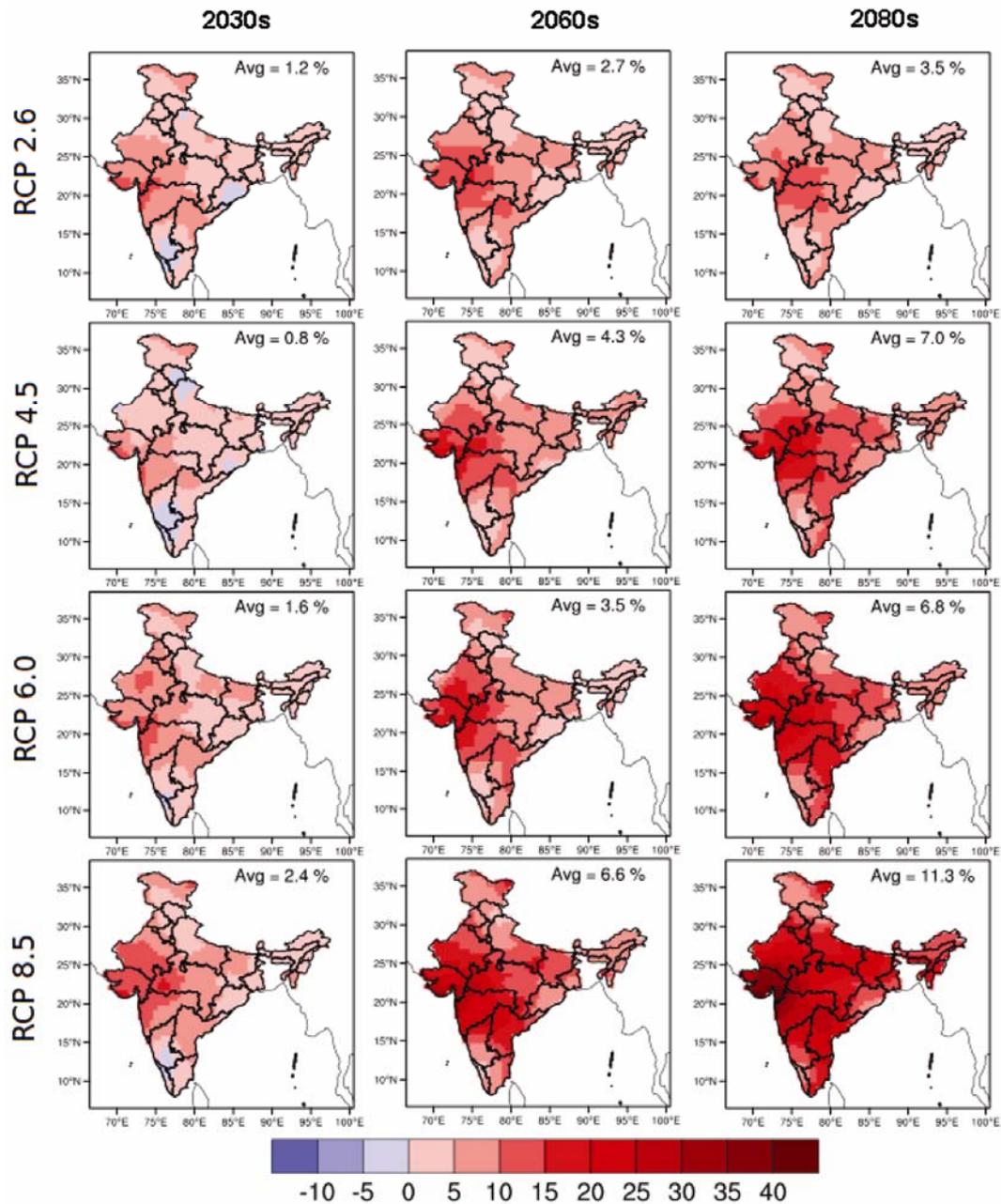
### Model agreement for the precipitation projections

Taylor diagram (Figure 2) suggests that model performance is more reliable for temperature simulations than for precipitation. To further study the reliability of precipitation projections from the CMIP5 models over India, in Figure 8 we show the number of models (out of 18) agreeing in the sign of the precipitation change projected for each grid over

India, for all the RCP scenarios. Figure 8 shows that the model agreement in precipitation projections increases from RCP2.6 to RCP8.5, and also the model agreement gets stronger from short- to long-term projections; thereby indicating that long-term projections are generally more reliable than their short-term counterparts. Figure 8 suggests that by 2080s under RCP8.5 on an average at least 14 models (more than 80% of GCMs) agree in the sign of precipitation change over India and in many of the regions, especially along central and eastern India, almost all the models agree in the sign of precipitation change. These results from CMIP5 climatology are significant as CMIP3-based climate projections suggested that less than 66% of the GCMs agree in the direction of the precipitation change over the Indian region for the SRES A1B scenario<sup>14</sup>.

### Extreme precipitation events

The IPCC special report on weather extremes projects likely increase in the frequency of heavy precipitation in the 21st century over many areas of the globe<sup>15</sup>. Studies based on the observed precipitation records of India Meteorological Department (IMD) have shown that the occurrence of extreme precipitation events and their variability has already gone up in many parts of India<sup>16,17</sup>. We quantify the expected future change in extreme rainfall events over India by using the daily precipitation data from one of the CMIP5 models, i.e. MIROC-ESM-CHEM for RCP 4.5. We chose this model as it is one of the better performers on the Taylor diagram (Figure 2). Figure 9 shows the percentage increase in the number of days when precipitation exceeds various thresholds. We took 1861–1870 as the reference period. Our analysis



**Figure 7.** CMIP5 model ensemble mean precipitation change (%) projected for 2030s (2021–2050), 2060s (2046–2075) and 2080s (2070–2099) relative to the pre-industrial period (1880s, i.e. over 1861–1900).

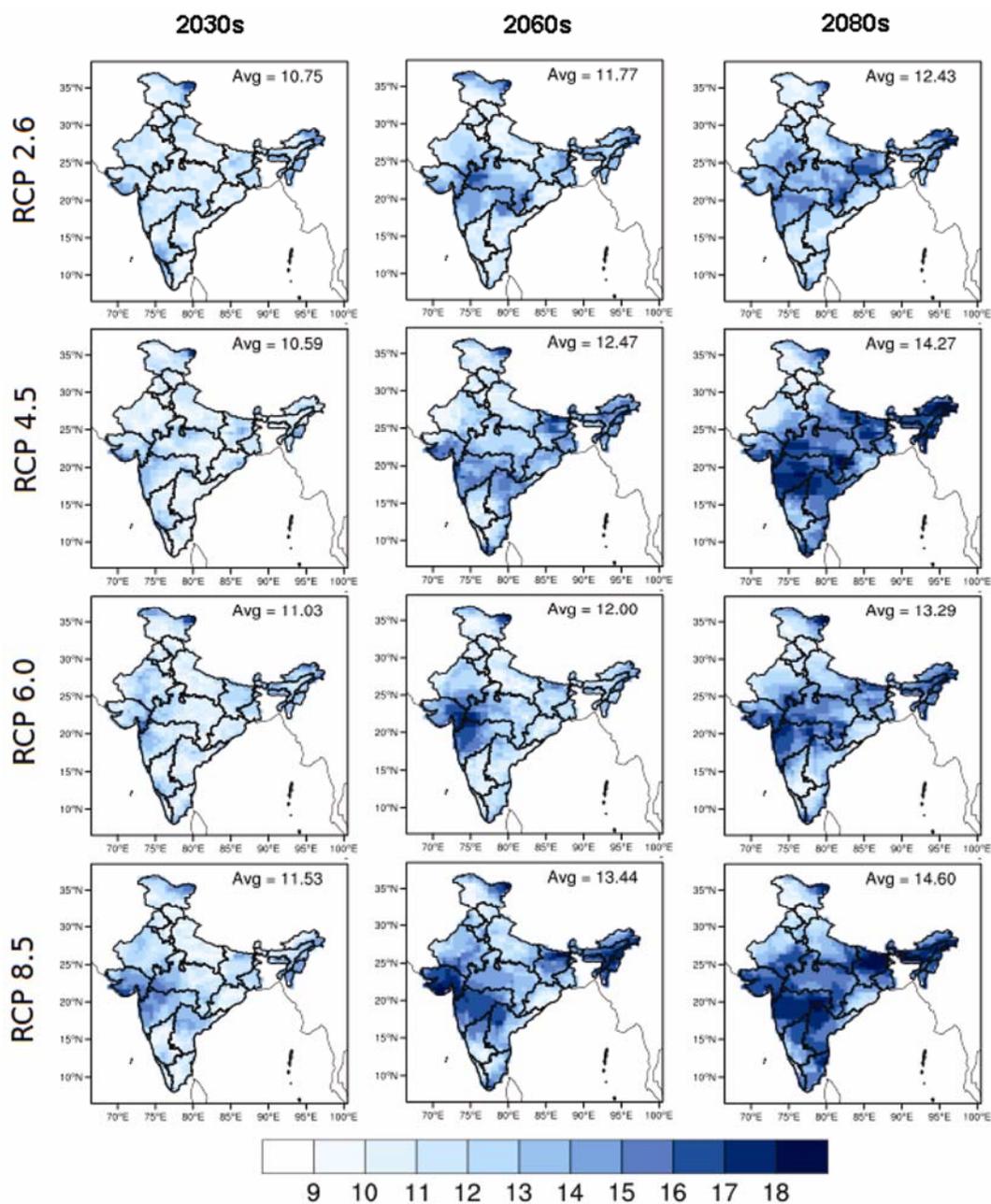
projects consistently increasing trends in frequency of extreme precipitation days (e.g. 40 mm/day) for decades 2060s and beyond (Figure 9). As can be seen, the changes in extreme precipitation events have not emerged as a clear signal in 2010s in this model. The decline in heavy-rainfall events in the 2050s is likely related to circulation changes on decadal variability in the model, which we intend to study in the future.

Available estimates in the literature<sup>5</sup> too suggest an increase in the rainfall intensity in the 21st century over most regions in India. It should be noted that the extreme precipitation analysis presented here is based on a single

GCM for a single RCP scenario. Multi-model and multi-scenario-based analysis of extreme precipitation events may yield different results.

## Discussion and conclusions

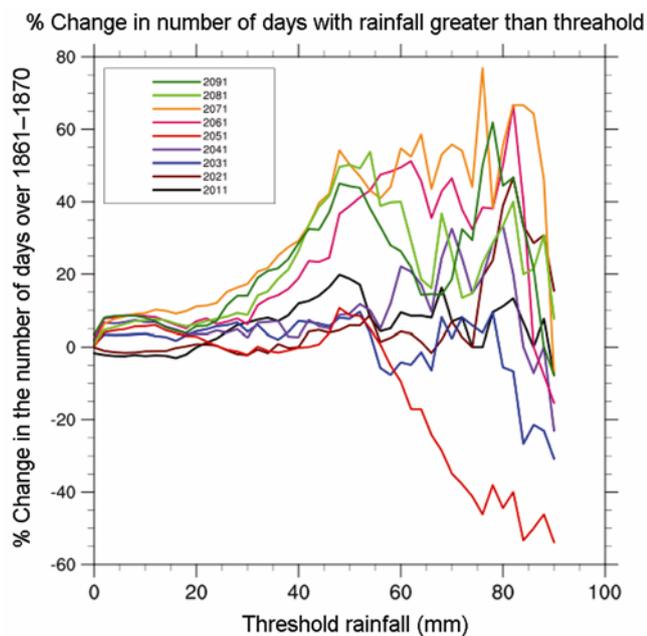
Climate change is recognized as the biggest challenge facing the planet<sup>18</sup>. The United Nations Framework Convention on Climate Change (UNFCCC) was adopted in May 1992 to primarily address the challenge of climate change – it aims to ‘achieve the stabilization of green-



**Figure 8.** Number of models agreeing in the sign of precipitation change projections for each grid for short (2021–2050), medium (2046–2075) and long (2070–2099)-term periods relative to pre-industrial period (1880s, i.e. over 1861–1900).

house gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. The Durban (2010) and Cancun (2011) agreements made at the 16th and 17th Conference of Parties of the UNFCCC recognized the need to hold the increase in global average temperature between 1.5°C and 2°C above pre-industrial levels. Out of the four scenarios discussed in this article, RCP2.6 is consistent with the goal of limiting warming at 2°C (ref. 19). However, an analysis by Arora *et al.*<sup>20</sup> indicates that 'limiting warming to roughly 2°C by the end of this century is "unlikely" since it requires an immediate ramp down of

emissions followed by ongoing carbon sequestration in the second half of this century'. The International Energy Agency also warns that the door of opportunity for limiting the warming below 2°C (450 ppm scenario) is fast closing and 'without further action by 2017 all CO<sub>2</sub> permitted for the 450 ppm stabilization scenario will be locked in by existing power plants, factories, buildings, etc.'<sup>21</sup>. We believe that the business-as-usual emission scenario lies somewhere between RCP6.0 and RCP8.5 (Figure 4). The CMIP5 ensemble projects a warming of about 3.3°C and 4.8°C over India (by 2080s relative to pre-industrial times) under the RCP6.0 and RCP8.5 scenarios respectively.



**Figure 9.** Projected change in the frequency of extreme rainfall days for future decades relative to the 1861–1870 baseline based on the MIROC-ESM-CHEM model for RCP4.5 scenario.

Climate change projections are associated with a range of limitations and uncertainties – driven mainly by the model and scenario uncertainties – as evident from the broad range of temperature projections for India, ranging from 1°C to 8°C over the period 1880–2099 under different RCP scenarios and even broader range of precipitation projections (Figure 3). Climate projections are generally more reliable at the global scale than at smaller regional scales<sup>22</sup>. In this analysis an effort has been made to illustrate the uncertainty by using CMIP5-based multiple model outputs in generating climate projections for India. It is expected that high-resolution multi-model regional climate change projections will be available for India in the near future through globally coordinated regional downscaling experiment (CORDEX). We expect that CORDEX-based regional climate projections will certainly bring more confidence to future climate projections for India<sup>9</sup>. In addition, we estimate that our bilinear extrapolation of climate projections to a common scale of  $0.5 \times 0.5$ , could likely introduce an error of magnitude 0.05% to our estimates.

The following are some of the major conclusions based on the results of this study.

(1) The CMIP5-based model ensemble mean for both temperature and precipitation is generally able to capture the broad distribution of observed climatology in India. However, our analysis suggests that the CMIP5-based temperature projections for India are far more reliable than the precipitation projections. Further, our model agreement index suggests that more and more climate models agree in the direction of the change in precipita-

tion for long-term projections than the shorter-term projections.

(2) This article provides temperature and precipitation projections for India based on 18 GCMs, for all the four RCP scenarios for the period 1880–2099. We find the ensemble mean climate to be closer to the observation than any individual models. The CMIP5-based model ensemble mean warming ranges from of 2°C (RCP2.6) to 4.8°C (RCP8.5) for India (from 1880s to 2080s), outlining the wide range of future climate change possibilities – driven by scenario uncertainties. All India precipitation is projected to increase by 6%, 10%, 9% and 14% under the scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5 respectively, by 2080s relative to the 1961–1990 base, whereas much larger variability is seen in the spatial distribution of precipitation.

(3) We find a consistent increase in the number of extreme rainfall days over the long term (2060s and beyond). However, consistency is lacking for daily extreme precipitation change over the short term.

(4) CMIP5 and RCP scenarios-based projections of future climate should be used for impact and vulnerability assessment and adaptation planning. Further, climate extremes also need to be considered in impact assessments and adaptation planning.

## Note

1. Ensemble member nomenclature with the triad of integers ( $N, M, L$ ) formatted as ( $r(N)i(M)p(L)$ ) distinguishes among closely related simulations by a single model. Different simulations that typically differ only by being started from equally realistic initial conditions are distinguished by different positive integer values of  $N$ . Simulations resulting from initializing a model with different methods are distinguished by assigning positive integer values of  $M$  and if there are many, closely related model versions, generally referred to as a perturbed physics ensemble (e.g. QUMP), then these are distinguished by a ‘perturbed physics’ number  $L$ , where the positive integer value of  $L$  is uniquely associated with a particular set of model parameters. In the ensemble nomenclature all the three values are required even if only a single simulation is performed<sup>28</sup>.

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ACKNOWLEDGEMENTS. R.K.C. thanks the Ministry of Environment and Forests, Government of India, for supporting this study in the form of the National Environmental Sciences fellowship. We thank the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and the climate modelling groups (listed in Table 2 of this article) for making available their model outputs.

Received 14 April 2012; revised accepted 31 July 2012