Simulated projections for summer monsoon climate over India by a high-resolution regional climate model (PRECIS)

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Impact of global warming on the Indian monsoon climate is examined using Hadley Centre's high-resolution regional climate model, PRECIS (Providing REgional Climates for Impact Studies). Three simulations from a 17-member Perturbed Physics Ensemble generated using Hadley Center Coupled Model (HadCM3) for the Quantifying Uncertainty in Model Predictions (QUMP) project, are used to drive PRECIS. The PRECIS simulations corresponding to the IPCC-SRES A1B emission scenario are carried out for a continuous period of 1961–2098. The model shows reasonable skill in simulating the monsoon climate over India. The climate projections are examined over three time slices, viz. short (2020s, i.e. 2011–2040), medium (2050s, i.e. 2041–2070) and long (2080s, i.e. 2071–2098). The model projections indicate significant warming over India towards the end of the 21st century. The summer monsoon precipitation over India is expected to be 9–16% more in 2080s compared to the baseline (1970s, i.e. 1961–1990) under global warming conditions. Also, the rainy days are projected to be less frequent and more intense over central India.

Keywords. Climate change, monsoon, regional climate model, simulated projections.

Introduction

THE climate of South Asia is dominated by the monsoon, which returns with remarkable regularity each summer and provides the rainfall needed to sustain over 60% of the world's population. More than 75% of the annual rainfall in India is received during four monsoon months, June through September. Climate change can therefore have a profound impact on different sectors like agriculture, human health, water resources, forestry, etc. through its influence on the monsoon-dominant climate over India[1]. Hence there is a widely felt need for understanding the nature of climate change over this part of the globe.

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Our current level of understanding of the components of the climate system and their interactions has reached an advanced stage, with the availability of a hierarchy of coupled ocean–atmosphere-sea–ice-land-surface models to provide indicators of global response as well as possible regional patterns of climate change. A variety of experiments have been performed by different modelling groups in the world to simulate expected climate change patterns under different emission scenarios prepared under the Intergovernmental Panel on Climate Change (IPCC) coordination[2]. Prominent among the scenarios are the IS92a and Special Report on Emission Scenarios (SRES), for which extensive model simulated data are made available to the climate-change research community. While global atmosphere–ocean coupled models have provided good representations of the planetary-scale features, their application to regional studies is often limited by their coarse spatial resolution (~ 300 km). For example, global models do not represent realistic topographical features like the Western Ghats along the west coast of India and consequently fail to reproduce their predominant influence on the monsoon rainfall patterns over India. However, developing high-resolution models on a global scale is not only computationally expensive for climate change simulations, but also suffers from the errors due to inadequate representation of high-resolution climate processes on a global scale. It is in this context that the regional climate models (RCMs) provide an opportunity to dynamically downscale global model simulations to superimpose the regional details of specific regions of interest. Rajendran and Kitoh[3] have used a super high-resolution global model to study the impact of global warming on the Indian summer monsoon. Their analysis shows spatially varying rainfall projection, with widespread increase in rainfall over interior regions and significant reduction in the orographic rainfall over the coastal regions of Kerala and Karnataka, and the eastern hilly regions around Assam.

However, not many studies are available over the Indian regions that study the climate change scenarios using simulations from high-resolution models. This study attempts to examine the projected future changes in the monsoon climate over India using a set of three Providing REgional Climates for Impact Studies (PRECIS) simulations made with the lateral boundary data from the Quantifying Uncertainty in Model Predictions (QUMP) simulations of UK Met Office.

Perturbed physics ensemble

To develop the high-resolution climate change scenarios for impact assessment studies, a high-resolution regional climate model, PRECIS, developed by the Hadley Centre, UK is run at the Indian Institute of Tropical Meteorology (IITM), Pune, at 50 km × 50 km horizontal resolution over the South Asian domain. The basic aspects explicitly handled by the model are briefly outlined in Noguer *et al.*[4]. Previously we have made simulations with PRECIS using the lateral boundary data from a high-resolution atmospheric GCM (150 km) called HadAM3H in so-called 'time slice' experiments and climate change scenarios have been generated for the baseline (1961–1990) and for 2080s (2071–2100) corresponding to IPCC-SRES A2 and B2 emission scenarios. Climate change assessments made for India based on these simulations are available in one of our earlier publications[5]. Here, three simulations from a 17-member perturbed physics ensemble (PPE) produced using HadCM3 under the QUMP project of Hadley Centre Met Office, UK, have been used as lateral boundary conditions (LBCs) for the 138-yr simulations of the regional climate model, PRECIS. Unlike the previous simulations, which correspond only to one distant future time slice, these continuous simulations provide an opportunity to assess the impact of climate change on the Indian monsoon for three time slices representing the near, medium and long term with implications for policy on these timescales.

The perturbed physics approach was developed in response to the call for better quantification of uncertainties in climate projections (Chapter 14 of the Third Assessment Report (TAR) of IPCC). The basic approach involves taking a single model structure and making perturbations to the values of parameters in the model, based on the discussions with scientists involved in the development of different parameterization schemes. In some cases, different variants of physical schemes may also be switched in and out. Any number of experiments that are routinely performed with a single model can then be produced in an 'ensemble mode', subject to constraints on computer time. A significant amount of perturbed physics experimentation has been done with HadCM3 and variants, starting with the work of Murphy *et al.*[6] and Stainforth *et al.*[7].

The QUMP simulations comprise 17 versions of the fully coupled version of HadCM3, one with the standard parameter setting and 16 versions in which 29 of the atmosphere component parameters are simultaneously perturbed[8].

Based on a preliminary evaluation of these 17 global runs for their ability to simulate the gross features of the Indian monsoon, the LBCs of three QUMP simulations, viz. Q0, Q1 and Q14 were made available by Hadley Centre, UK. Hence these three QUMP runs were carried out at IITM, Pune for the period 1961–2098 and are utilized to generate an ensemble of future climate change scenarios for the Indian region. These simulations are made at 50 km × 50 km horizontal resolution.

Current climate variability

Observed climate variability over India has been extensively studied and documented[9–12]. Here we provide a brief summary of the salient features of observed rainfall and temperature variability and change over India during the past century.

Observed rainfall variability

The Indian summer monsoon circulation dominates the rainfall over South Asia, and as such rainfall variability over the region is considered to be synonymous with monsoon variability. All-India summer monsoon rainfall (AISMR) displays predominant interannual variability, marked by recurrent large-scale droughts and floods. AISMR has a mean of 852 mm, with a standard deviation of 84 mm based on data during 1871–1990. Years of large-scale deficient and excess monsoon rainfall are identified with the criteria of the standardized AISMR being below –1 and above +1 respectively. Several studies during the last four decades have clearly pointed out that the monsoon rainfall is trendless and randomly fluctuates over a long period of time, particularly on an all-India scale[12]. However, some notable trends do exist on a smaller spatial scale[1,11,13]. On a decadal scale, AISMR is known to display an epochal pattern, with multi-decadal periods (3–4 decades each) alternating between relatively more frequent droughts and vice versa[12]. A reassuring feature of the Indian rainfall variability is that the Indian summer monsoon shows stable long-term characteristics with extremes such as droughts and floods being a part of its natural variability. We should also mention here that while the all-India average monsoon rainfall is trendless over an extended period starting 1871, it has been observed in recent years that the characteristics of daily rainfall have been undergoing changes in a way that the frequency and intensity of heavy to very heavy rainfall events are increasing, whereas the events with low rainfall are showing a decline in their frequency, particularly over the central parts of India[14]. This redistribution of daily rainfall character is probably making the seasonal total to be trendless though it can have implications for the way we conserve and utilize the water.

Observed temperature variability

All-India mean annual surface air temperatures over the past century indicate a significant warming of 0.51°C/ 100 yrs (refs 10, 15–18) with greater warming of 0.21°C/ 10 yrs during the post-1970 period. The warming in the annual mean temperatures is mainly contributed by the post-monsoon and winter seasons. The monsoon temperatures do not show significant trend over a major part of the country. The increase in the all-India mean temperatures is almost solely contributed by the increase in maximum temperatures with the minimum temperatures remaining practically trendless[17]. However, the warming trend in mean annual temperature in the recent three decades is contributed by both the maximum (0.20°C/10 yrs) and minimum (0.21°C/10 yrs) temperatures[16,18].

Model-simulated monsoon rainfall and its variability

The high-resolution regional simulations generated using PRECIS with LBCs from QUMP simulations, have been examined in detail to evaluate the model skills in representing the regional climatological features, especially the summer monsoon characteristics. Tables 1–3 give the seasonal rainfall and temperature statistics for the three simulations, viz. Q0, Q1 and Q14. Two of these simulations, viz. Q0 and Q14 have shown good skill in their ability to simulate the quantum of seasonal monsoon rainfall (879 and 864 mm respectively), whereas Q1 shows a dry bias (637 mm). The variability of the baseline monsoon rainfall is more in Q1 (71 mm) compared to Q0 (53 mm) and Q14 (66 mm). However, the simulated variability in all the three simulations is lower compared to the observed variability (97mm) in the baseline period.

Table 1. Characteristics of simulated seasonal and annual rainfall and mean temperature for all-India (baseline and A1B scenario – Q0 simulation) as simulated by of PRECIS

	Rainfall (mm)					Mean temperature (°C)				
Q0	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND	Annual
Mean										
Obs	27	120	954	132	1234	18.2	26.9	27.5	21.3	24.3
1970s	41	229	879	126	1275	14.7	26.5	24.8	16.8	21.5
2020s	37	219	911	136	1303	16.5	28.0	26.2	18.3	23.1
2050s	51	243	980	146	1421	18.2	29.4	27.1	19.8	24.4
2080s	51	243	1024	153	1471	19.3	30.6	28.3	21.2	25.6
Standard deviation										
Obs	10.3	23.3	97.3	28.8	114.7	0.5	0.5	0.3	0.4	0.2
1970s	18.1	50.6	53.0	27.1	74.0	1.1	0.7	0.6	1.0	0.4
2020s	22.2	49.0	54.8	41.2	79.9	0.9	0.9	0.8	1.3	0.6
2050s	34.2	63.9	67.8	50.4	102.7	1.2	0.9	0.8	1.2	0.6
2080s	25.7	69.0	60.9	43.4	101.4	1.0	0.7	0.6	1.0	0.4

MAM, March–April–May.

Table 2. Characteristics of simulated seasonal and annual rainfall and mean temperature for all-India (baseline and A1B scenario – Q1 simulation) as simulated by PRECIS

	Rainfall (mm)					Mean temperature (°C)				
Q1	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND	Annual
Mean										
1970s	42	184	637	98	961	15.8	26.5	25.8	17.5	22.3
2020s	37	199	678	95	1009	17.4	28.1	26.6	18.5	23.4
2050s	41	198	669	101	1009	18.8	29.0	27.8	20.5	24.8
2080s	43	199	734	108	1084	19.8	30.2	28.6	21.7	25.8
Standard deviation										
1970s	15.6	31.7	71.5	23.4	79.4	0.9	0.7	0.7	0.9	0.6
2020s	12.3	38.7	61.6	21.1	87.5	0.7	0.9	0.9	1.3	0.8
2050s	14.1	36.6	89.5	23.1	96.3	1.1	0.7	0.7	1.1	0.6
2080s	18.9	31.4	100.2	28.0	107.1	1.1	0.7	0.9	1.2	0.7

Table 3. Characteristics of simulated seasonal and annual rainfall and mean temperature for all-India (baseline and A1B scenario – Q14 simulation) as simulated by PRECIS

	Rainfall (mm)					Mean temperature (°C)				
Q14	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND	Annual
Mean										
1970s	70	218	864	141	1293	15.4	27.0	25.5	18.1	22.3
2020s	61	242	910	145	1358	17.2	28.5	26.7	19.6	23.8
2050s	64	248	940	148	1400	18.8	30.4	28.1	21.8	25.5
2080s	75	252	941	174	1442	19.8	31.3	29.3	22.7	26.6
Standard deviation										
1970s	37.8	47.2	66.6	39.1	102.8	0.93	0.76	0.53	0.82	0.41
2020s	19.9	39.3	83.7	44.6	90.3	1.1	0.66	0.66	0.85	0.44
2050s	26.1	33.9	79.8	49.4	107.6	1.31	0.7	0.71	1.25	0.6
2080s	39.2	65.0	85.6	46.6	117.2	1.2	1.07	0.69	0.97	0.63

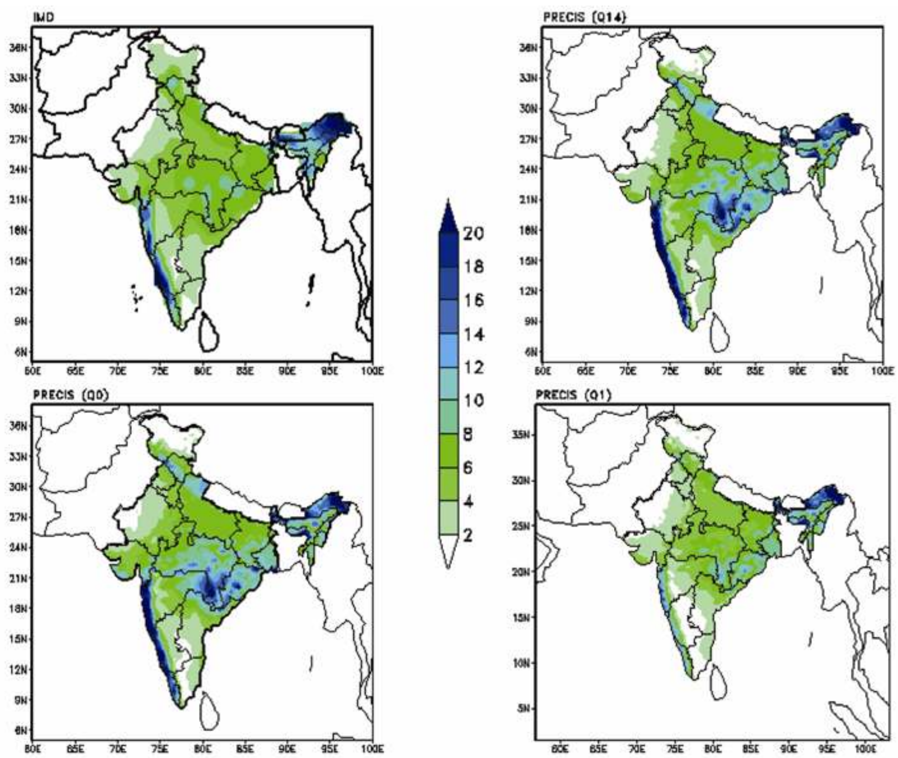

Figure 1. Spatial patterns of summer monsoon rainfall climatology as simulated in the three simulations of PRECIS (Q0, Q1 and Q14). The observed monsoon rainfall climatology (Obs) is based on the gridded India Meteorological Department (IMD) rainfall data. The climatologies correspond to the period 1961–1990.

The spatial patterns of seasonal rainfall as simulated by PRECIS for the baseline period are shown in Figure 1. The high-resolution ($1° \times 1°$ lat./long.) daily gridded rainfall dataset for the Indian region for 1951–2007 prepared by India Meteorological Department (IMD) based on 1803 stations, well distributed over India[19], has been used for the evaluation of model skill. The rainfall maximum over the West coast of India and the rain-shadow region in the southeastern peninsula are well simulated by the model. The baseline simulations seem to provide an adequate representation of the current pattern. However, there exist some quantitative biases in the simulated rainfall. A substantial wet bias is simulated over the west coast and east central India in the baseline simulation of ensembles Q0 and Q14. Precipitation over the Bay of Bengal region is overestimated in the model simulations (not shown in Figure 1) in all the three simulations. A dry bias of around 8–10 mm/day is simulated in the baseline simulation of Q1 over the west coast.

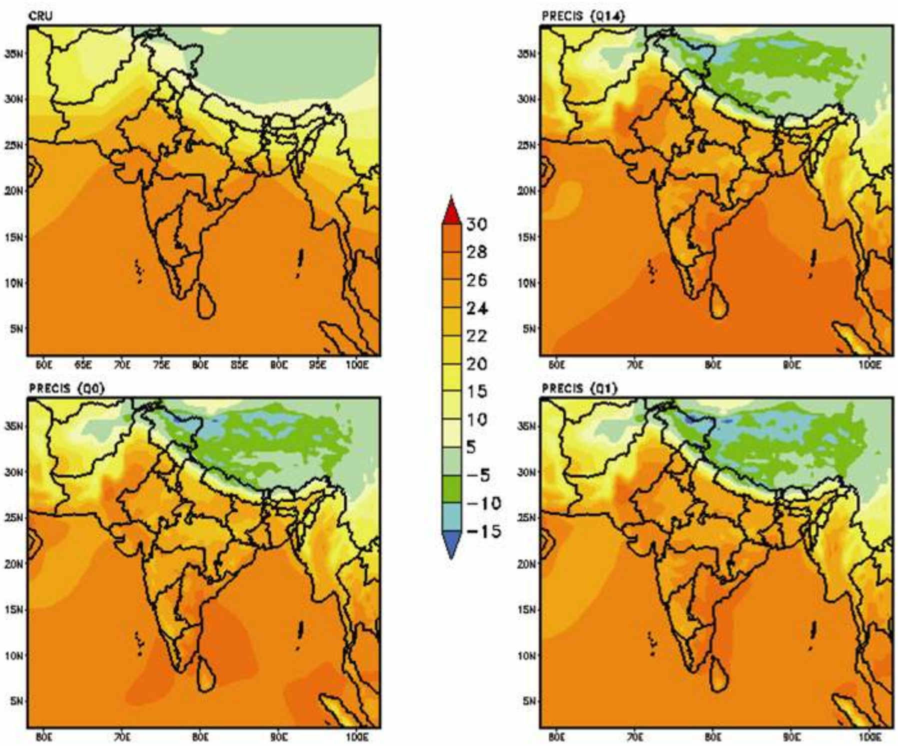

Figure 2. Spatial pattern of mean annual surface air temperature simulated in PRECIS compared with CRU (Climate Research Unit, UK) temperature data (1961–1990).

Model-simulated annual mean temperature and circulation

The mean annual surface air temperature simulated by the model is shown in Figure 2. There exists a warm bias over southern India, especially in Tamil Nadu and Andhra Pradesh, whereas cold bias exists in the northern states like Jammu and Kashmir, Himachal Pradesh and parts of Uttar Pradesh along the foothills of the Himalayas. Examination of the simulated mean temperatures during different seasons indicates that the temperature maximum over northwest India during pre-monsoon season is well reproduced in the model (figure not shown). The model also has some cold bias in the seasonal surface air temperatures, as shown in Table 1. The variability of the seasonal temperatures is more in the model simulations compared to the observed temperatures. Other characteristics of monsoon, like the low-level circulation and monsoon trough, are also well represented in the model (figure not shown). However, the model-simulated baseline mean sea-level pressure in the monsoon trough region is lower compared to the observed pressure in all the three ensembles.

Simulated annual cycles

The mean annual cycles of the simulated and observed all-India area averaged rainfall and surface air temperature are shown in Figure 3. The model captures the general march of the annual cycle of rainfall reasonably well. However, the model produces more precipitation during the pre-monsoon months of March, April and May. The model somewhat underestimates the rainfall during the monsoon months. The annual cycle in the surface air temperature, having the highest temperature during the pre-monsoon months followed by an abrupt fall during the monsoon months, is well represented by PRECIS.

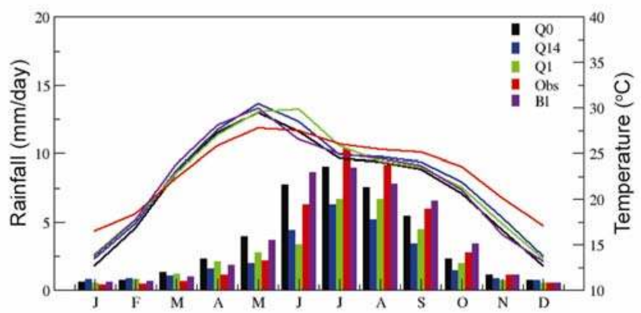

Figure 3. Annual cycles of all-India mean rainfall (bars) and surface air temperature (lines) for the QUMP simulations (Q0, Q1 and Q14) compared with observed (Obs) and baseline (Bl) (a PRECIS simulation made earlier with LBCs from HadAM3H).

However, there appears to be a significant warm bias in the temperature during the pre-monsoon months and the onset phase of the monsoon. The temperature is underestimated thereafter from the month of July, in all the three

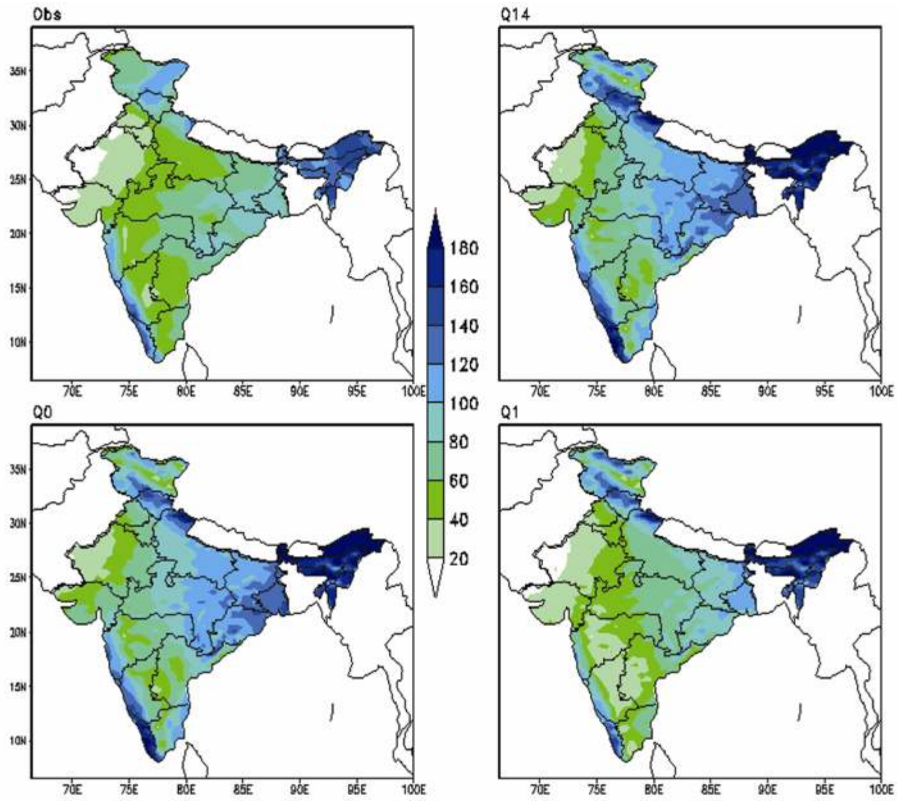

Figure 4. Number of rainy days as simulated by PRECIS compared with observed rainy days using IMD gridded dataset for the period 1961–1990.

ensemble simulations. However, these biases could be partly due to the relatively coarse network chosen for representing the observed temperatures or due to the lack of observations in high-altitude regions in the country, which are otherwise covered while working out the annual cycle with model simulations.

Analysis of extreme events

Recent studies on climate change have shown that besides the change in the mean climate, the extreme weather elements will also be impacted by global warming[20]. In this context, we have analysed here the frequency and intensity of rainy days over India to assess the likely changes in future, if any. Among temperature extremes, we have analysed the highest daily maximum temperature and lowest daily minimum temperature.

Precipitation events

Any day with rainfall greater than 2.5 mm is considered as a rainy day. Figure 4 shows the observed number of rainy days (top left panel) compared with the model simulated rainy days in Q0, Q1 and Q14 simulations (other three panels) for the period 1961–1990. The daily gridded rainfall data from IMD are used here for model evaluation. In baseline simulations, the frequency of rainy days is more in east and northeast India and less over western India (Figure 4). The model results are similar to the observed pattern, as can be seen from Figure 4. The intensity of rainfall on a rainy day is more along the Western Ghats and over northeast India (Figure 5) and matches well with the observed intensity pattern.

Extreme temperature events

Extremes in temperature are generally characterized by the frequency and intensity of daily temperatures exceeding certain tolerable limits. Baseline simulations shown in Figures 6 and 7 are in general agreement with the observed patterns. The model simulates the highest maximum temperatures of more than 45°C in the northwestern and central parts of India (Figure 6). The highest maximum temperatures between 40°C and 45°C are simulated over the west coast and adjoining areas.

Lower values of lowest minimum temperatures (Figure 7) are recorded over the extreme northern parts of India in the range –15°C to –10°C. The temperatures increase from north to south and they range between –15°C and 10°C. The northwestern parts of India have experienced annual extreme minimum temperatures in the range 0°C to

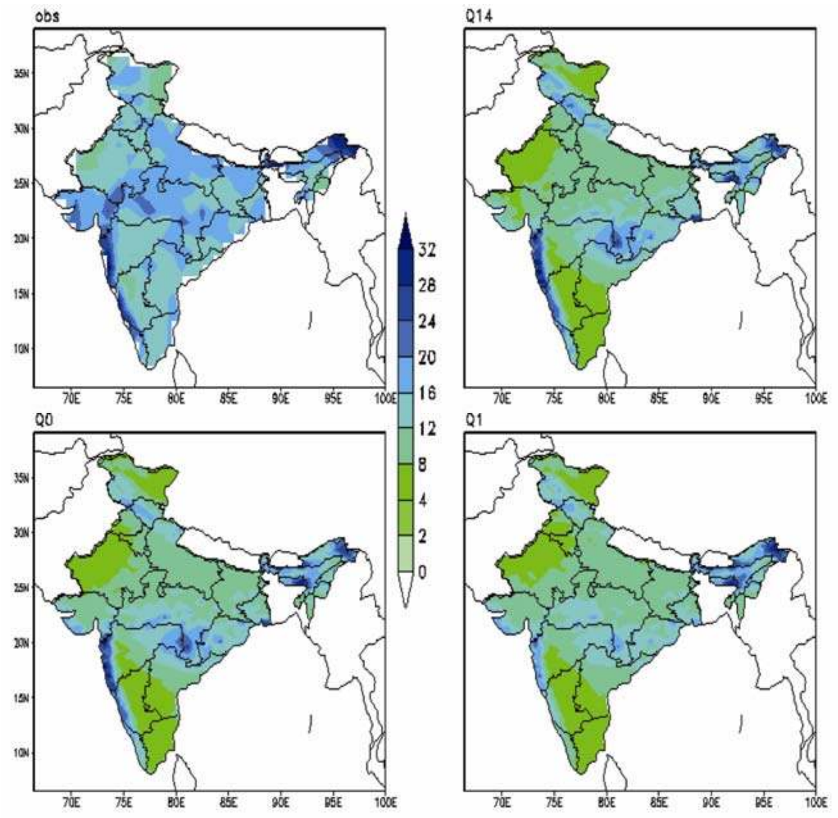

Figure 5. Intensity of rainfall (mm/day) on a rainy day as simulated in the three runs compared with observed values derived using IMD gridded dataset for the period 1961–1990.

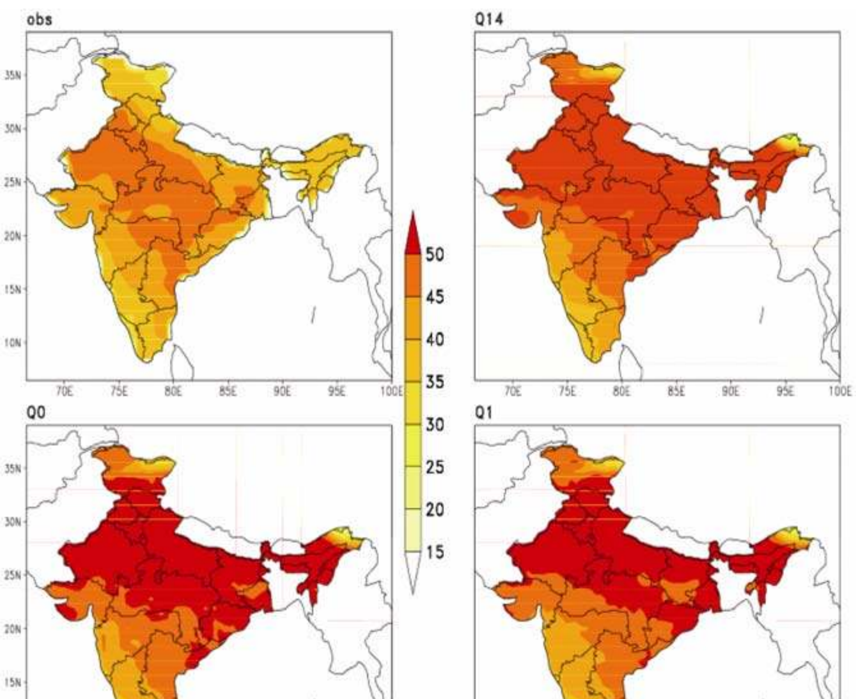

Figure 6. Patterns of simulated highest daily maximum temperature (°C) compared with observations based on IMD gridded temperature dataset for the period 1961–1990.

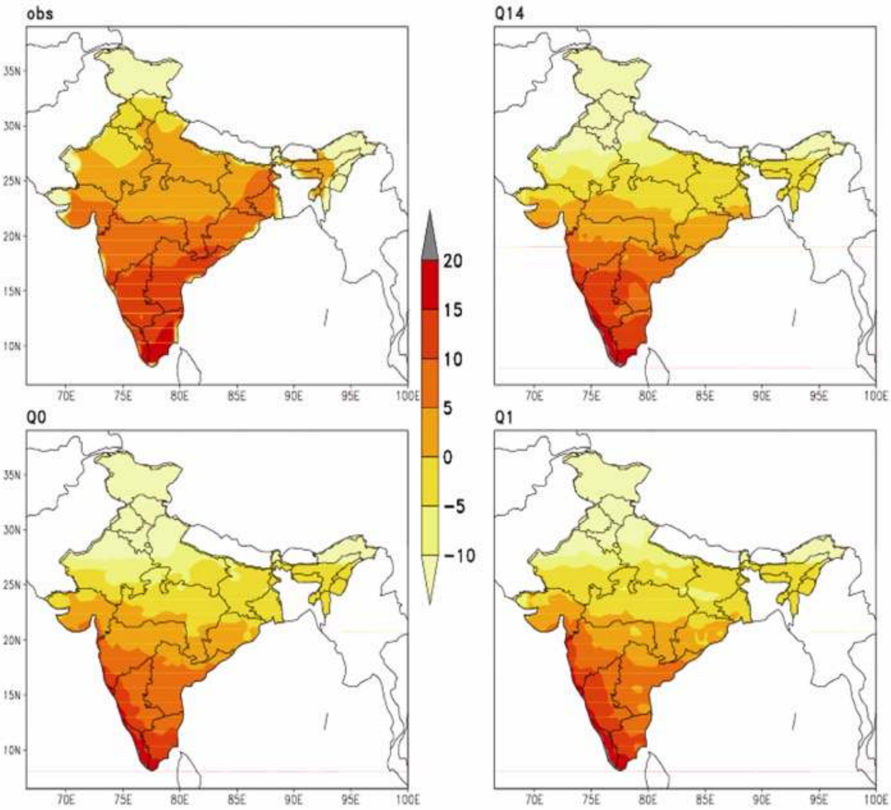

Figure 7. Same as Figure 6, but for the lowest daily minimum temperature.

–5°C. Greater values of the lowest minimum temperatures (about 15°C) are observed over the southern parts of peninsular India. The lowest minimum temperatures in baseline simulations increase from north to south in all the three simulations, Q0, Q1 and Q14. There is a good agreement in the spatial patterns of the three ensemble simulations. The lowest minimum temperatures of less than –5°C are seen over northwest, extreme northeast and extreme north India, in all the three baseline simulations. The higher values of lowest minimum temperatures over the peninsula match well with the observed values. In general, the model simulates warm bias in maximum temperatures and cold bias in minimum temperatures.

Projections of future climate

Simulated percentage changes in mean monsoon precipitation in the 2020s, 2050s and 2080s with respect to baseline (1961–1990) are shown in Figure 8 for all the three simulations. Q0, Q1 and Q14 simulations project 16%, 15% and 9% rise respectively, in the monsoon rainfall at the all-India level, towards the end of the 21st century. However, the projections indicate a slight decrease in monsoon rainfall over Tamil Nadu and Andhra Pradesh towards the end of the 21st century. These three simulations indicate a possibility for higher monsoon rainfall in future for all other states. However, more such simulations are needed to gain confidence in the assessments of the expected future changes on smaller regional scales. PRECIS simulations for the 2020s, 2050s and 2080s indicate an all-round warming over the Indian subcontinent associated with increasing greenhouse gas concentrations (Figure 9). The annual all-India mean surface air temperature rise by the end of the century ranges from 3.5°C to 4.3°C in the three simulations (Tables 1–3).

Figure 10 gives the annual cycles of rainfall and surface air temperature for the three time slices, viz. 2020s, 2050s and 2080s. The model indicates a positive change in rainfall in future, especially during the monsoon months. This increase is seen in all the three simulations, except, for the June rainfall simulated by the Q0 simulation. The projected changes of about 4–5°C towards the 2080s are seen for different months in all three simulations, except the monsoon months of Q1 simulation where the projected changes in temperature are nearly 3°C.

Changes in extreme precipitation events

From the three simulations it appears that the number of rainy days and the intensity of rainfall on a rainy day may change in future in response to global warming. The projected number of rainy days shows a non-uniform change over India. The spatial pattern of projections also differs

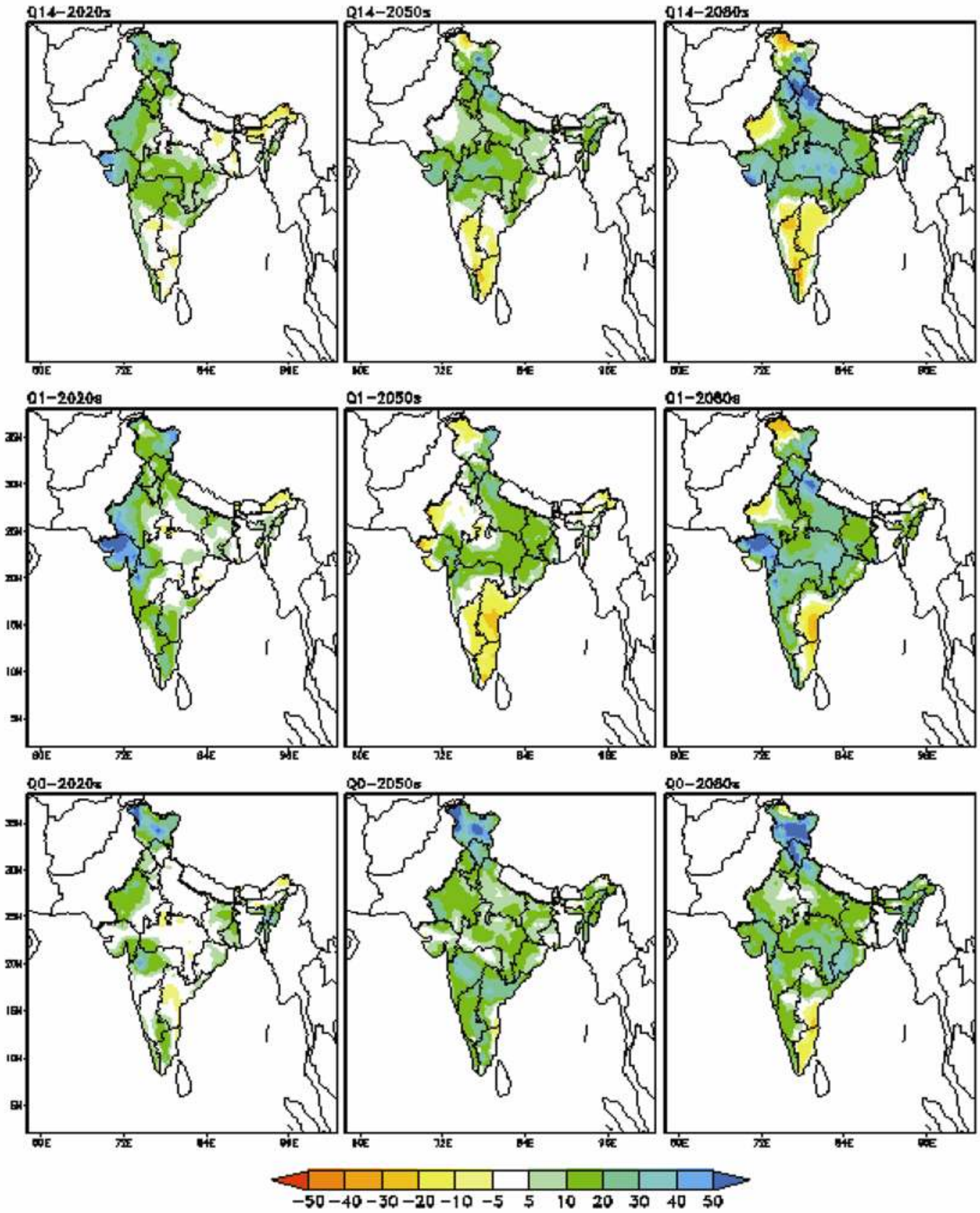

Figure 8. Projected future changes in mean monsoon precipitation (%) in the 2020s, 2050s and 2080s with respect to the baseline period of 1961–1990.

among ensembles, suggesting the uncertainty in the projections of the changes in the number of rainy days. In near future, i.e. 2020s, Q0 and Q14 show decrease in the number of rainy days over the west coast, central India and the Indo-Gangetic plains and increase over northwest India and the east peninsula. Q0, on the other hand, indicates increase in the number of rainy days everywhere, except northeast and east central India. In 2050s, Q1 and Q14 depict decrease in the number of rainy days over major part of the country, whereas Q0 shows decrease over Uttar Pradesh, Bihar, Jharkhand and northeast India only. Towards 2080s, the number of rainy days may increase everywhere except northwest India in the Q14 simulations, whereas Q0 and Q1 show increase over the west coast and decrease over central India (Figure 11).

On the other hand, all the three simulations indicate increase in the rainfall intensity in the 21st century over most regions in the country. The rise in intensity is projected to be more in central India, as can be seen from Figure 12. Marginal decrease in the intensity may also be seen in the east peninsular region in some simulations.

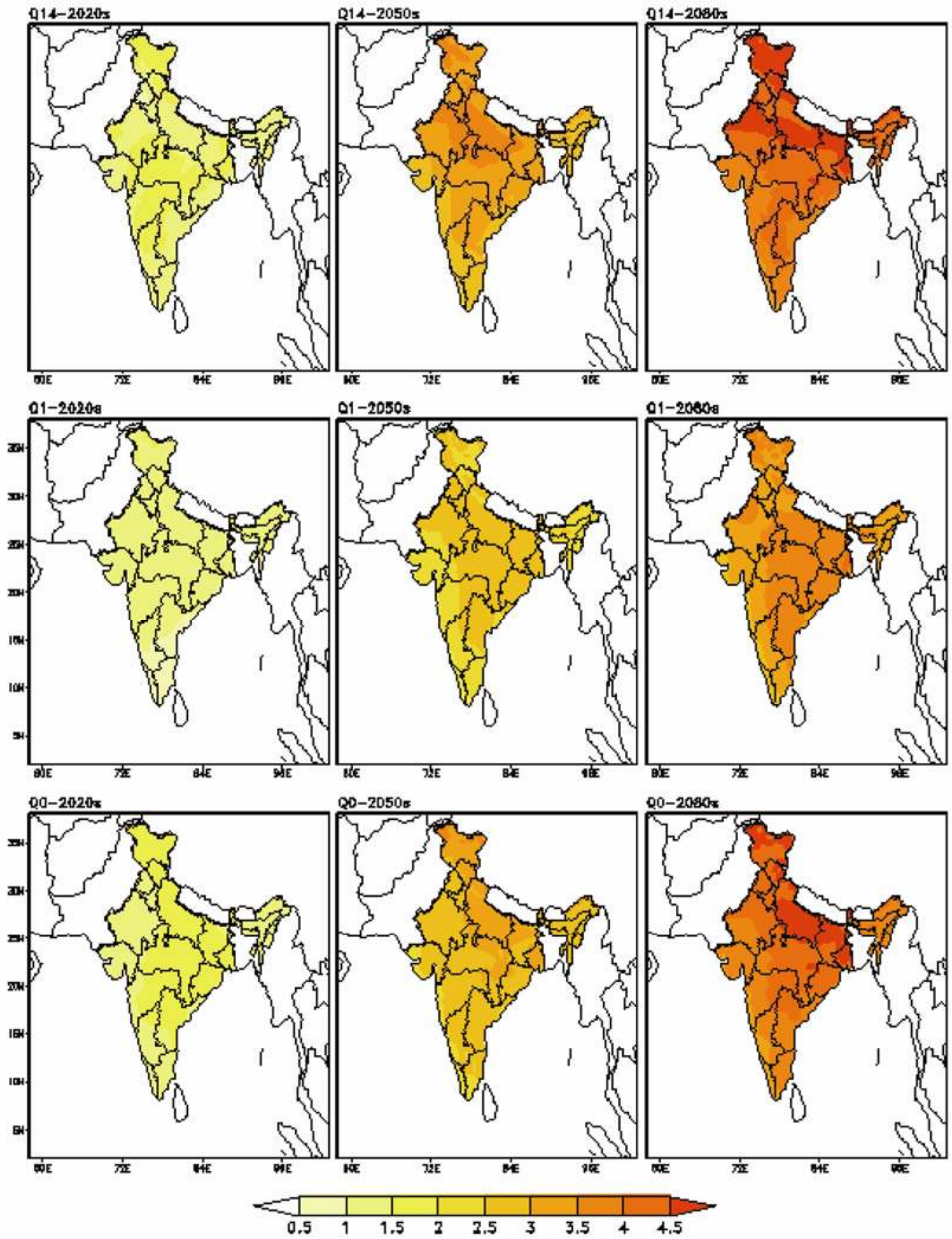

Figure 9. Projected future changes in mean annual surface air temperature (°C) in the 2020s, 2050s and 2080s with respect to baseline (1961–1990).

Changes in extreme temperature events

The analysis of the three model simulations indicates that both the daily extremes in surface air temperature may intensify in the future. The spatial pattern of the change in the highest maximum temperature (Figure 13) suggests a warming of 1–4°C towards the 2050s, which may exceed even 4.5°C in most places towards the end of the 21st century. The rise in the night-time temperatures (Figure 14) is even more in all the three time slices compared to the daytime temperatures. A rise of more than 4.5°C in night-time temperatures may be seen throughout India, except some small pockets in the peninsula.

Summary

This article presents an assessment of the expected future changes in the characteristics of rainfall and temperature

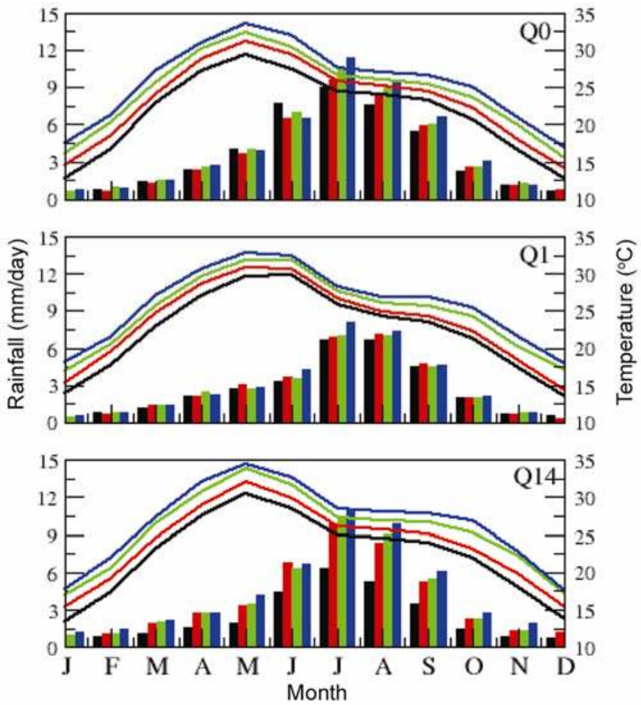

Figure 10. Annual cycles of all-India mean rainfall (bars) and surface air temperature (lines) simulated by PRECIS for 1970s (black), 2020s (red), 2050s (green) and 2080s (blue).

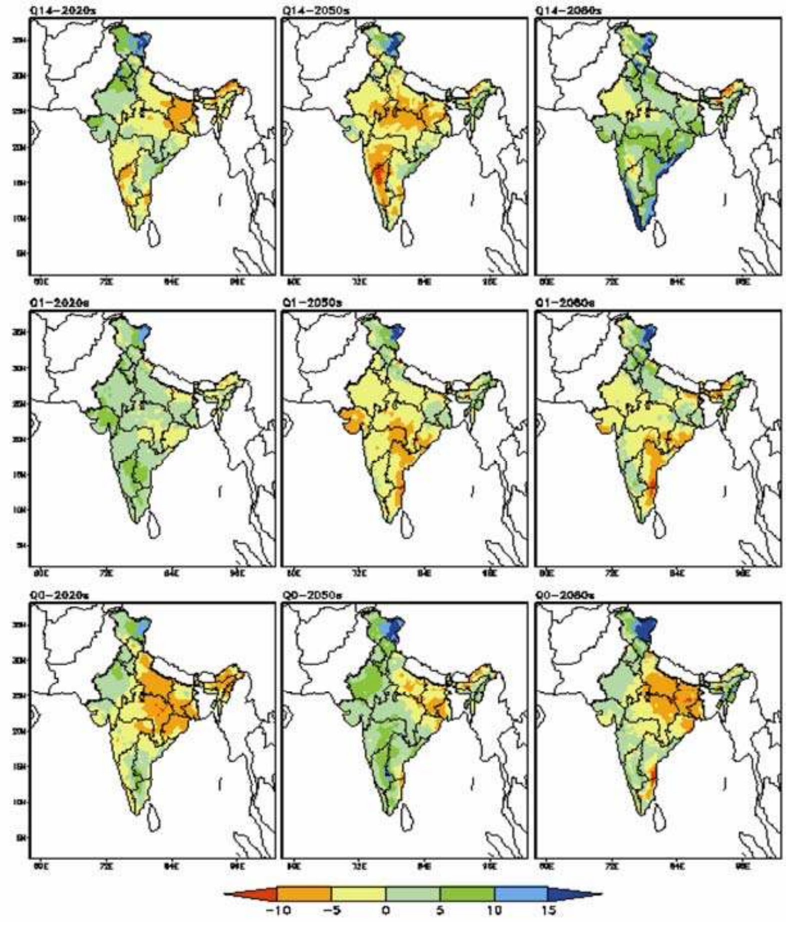

Figure 11. Projected future changes in the number of rainy days in the 2020s, 2050s and 2080s with respect to the baseline (1961–1990) in the three simulations.

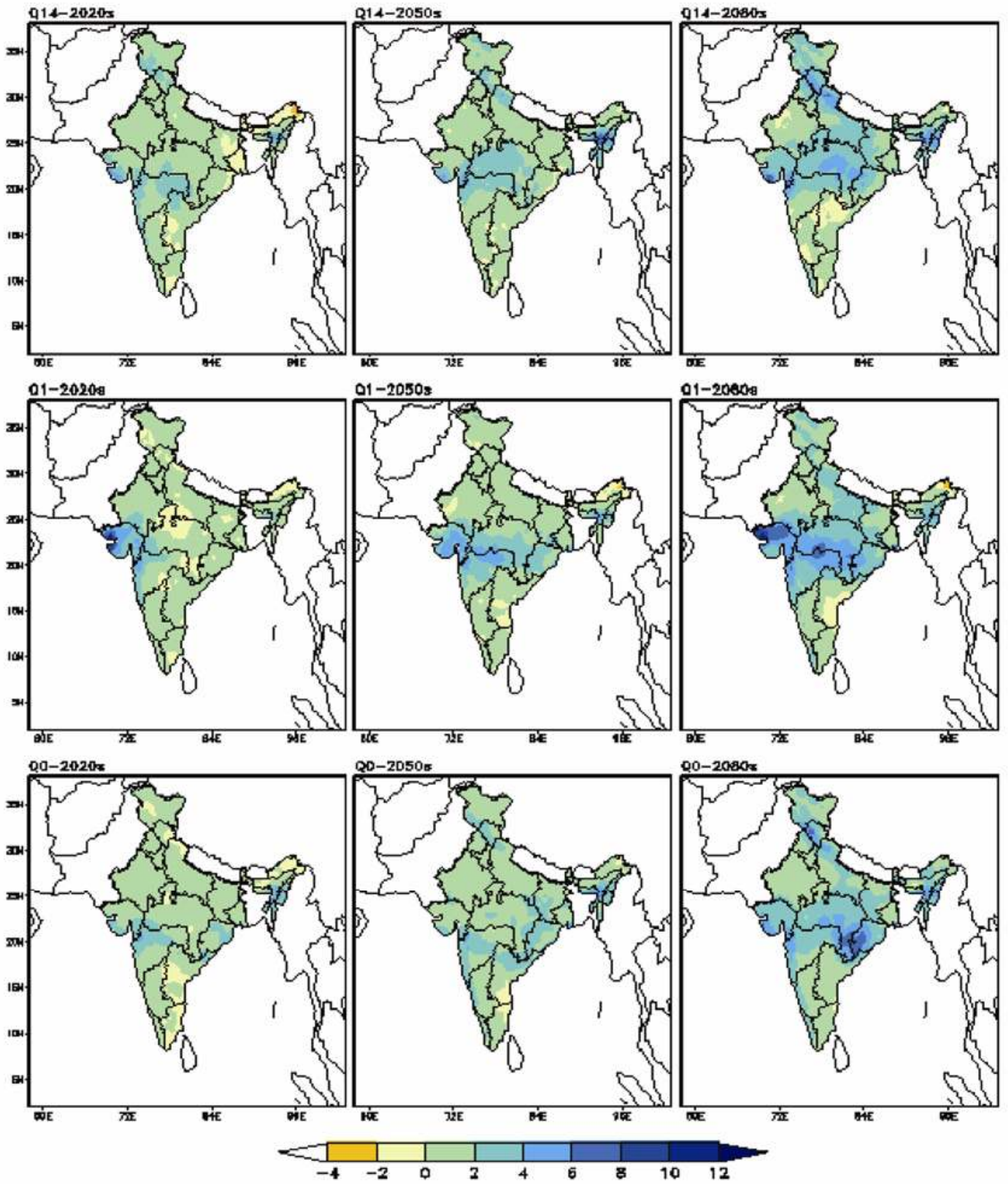

Figure 12. Projected changes in the intensity of rainfall on a rainy day (mm/day) in the 2020s, 2050s and 2080s with respect to the baseline (1961–1990) in the three simulations.

over India under a global warming scenario (IPCC SRES-A1b) based on three 138-year (1961–2098) simulations made using PRECIS. Some of the major findings from these three simulations that are driven by the LBCs derived from a large ensemble of QUMP simulations are:

- High-resolution regional climate model (PRECIS) showed good skill in representing the seasonal mean as well as some small-scale features of monsoon over India.
- Towards the end of the 21st century (2071–2098) all three simulations indicate a significant rise in the mean annual surface air temperature (~ 4°C) over India.
- The summer monsoon precipitation may increase by ~ 15% over India towards the 2080s relative to the baseline period corresponding to the 1970s. But on smaller regional scale, some regions may experience slightly lower rainfall compared to the baseline period in the future.
- The projected change in the number of rainy days may be non-uniform over the country. The spatial pattern of projections also differs among ensembles, suggesting uncertainty in the projection of changes in the number of rainy days. However, the intensity of rainfall on a rainy day is likely to be higher in the future.

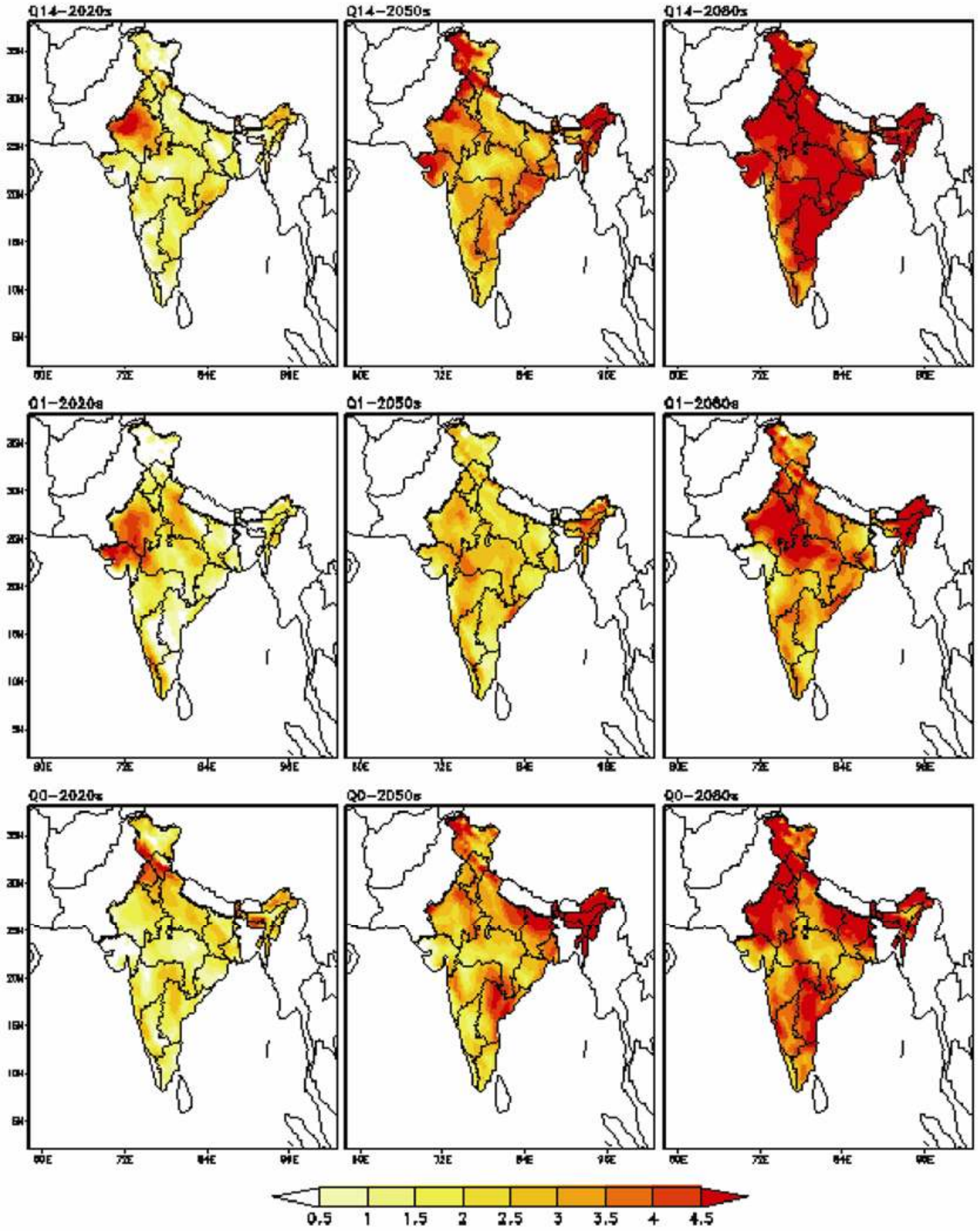

Figure 13. Projected future changes in the highest daily maximum temperatures (°C) in the 2020s, 2050s and 2080s with respect to the baseline (1961–1990) in the three simulations.

- The analysis of temperature extremes indicates that both the daily maximum and minimum temperatures may be intense in the future under global warming conditions.
- Changes in the night-time temperature extremes may be more intense than those of daytime temperatures.

The scenarios presented in this article are indicative of the expected range of changes in the climate over the Indian region. It must be noted that the quantitative estimates still have large uncertainties associated with them due to limited number of high-resolution regional model simulations available at this stage. We recognize the limitations of these projections based on a small number of simulations from one regional climate model. It is expected that in the near future, more high-resolution regional simulations will be available through globally coordinated regional downscaling experiment (CORDEX)

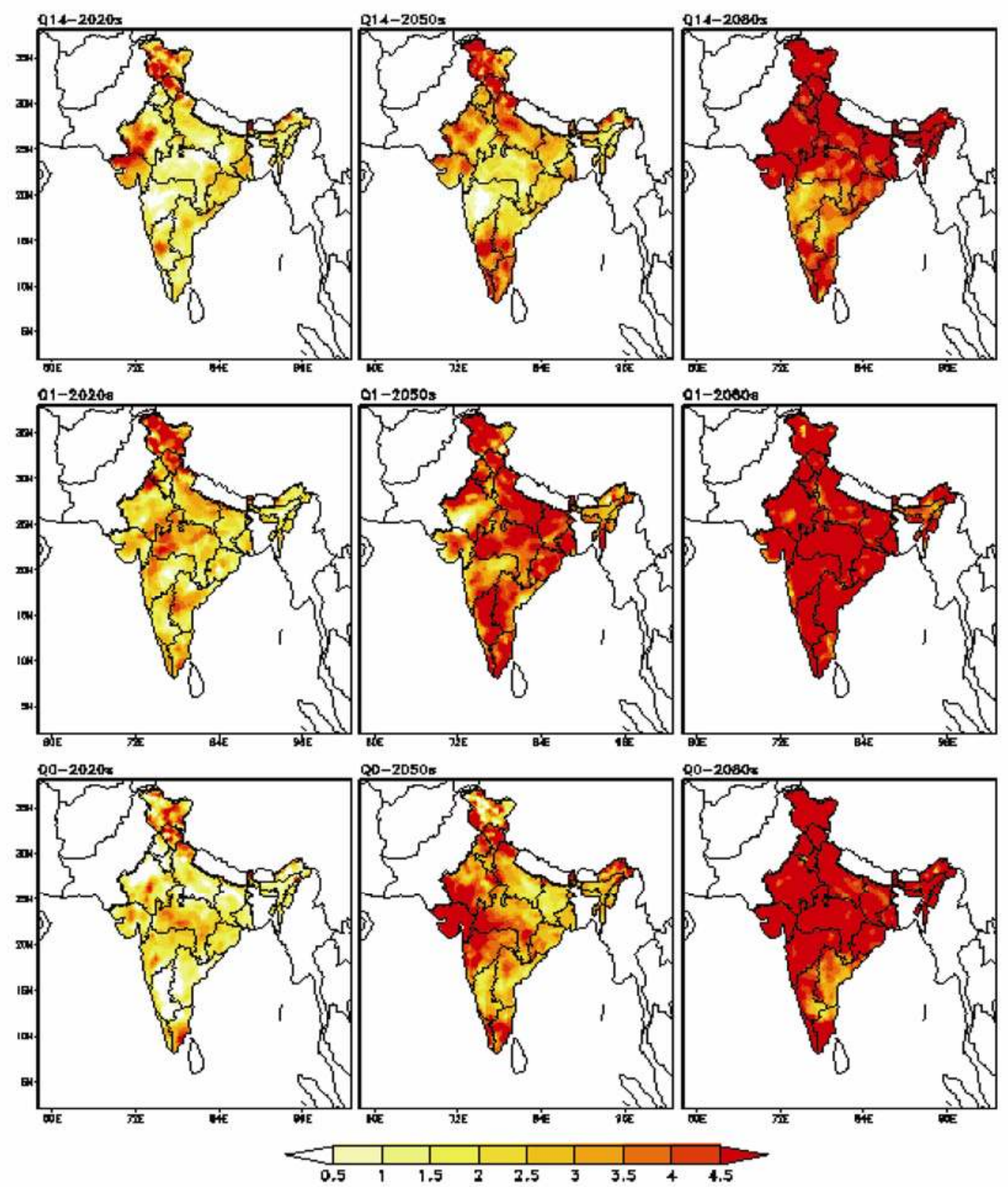

Figure 14. Same as Figure 13, but for the daily lowest minimum temperatures.

not only from PRECIS, but also from other regional climate models. This, we believe, will allow us to quantify the uncertainties better and also gain more confidence in the projected future climate over the country.

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