Hindawi Publishing Corporation
Advances in Meteorology
Volume 2011, Article ID 138425, 11 pages
doi:10.1155/2011/138425

Research Article

Characteristic Features of Precipitation Extremes over India in the Warming Scenarios

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Received 27 December 2010; Accepted 24 March 2011

Academic Editor: Eugene Rozanov

The detection of possible changes in extreme climate events, in terms of the frequency, intensity as well as duration assumes profound importance on the local, regional, and national scales, due to the associated critical socioeconomic consequences. Therefore, an attempt is made in this paper to evaluate various aspects of future projections of precipitation extremes over India, as projected by a state-of-art regional climate modeling system, known as PRECIS (Providing REgional Climates for Impacts Studies) towards the end of the 21st century (that is, 2071–2100) using standardized indices. Study reveals that PRECIS simulations under scenarios of increasing greenhouse gas concentration and sulphate aerosols indicate marked increase in precipitation towards the end of the 21st century and is expected to increase throughout the year. However the changes in daily precipitation and the precipitation extremes during summer monsoon (June through September) season are prominent than during the rest of year. PRECIS simulations under both A2 and B2 scenarios indicate increase in frequency of heavy precipitation events and also enhancement in their intensity towards the end of the 21st century. Both A2 and B2 scenarios show similar patterns of projected changes in the precipitation extremes towards the end of the 21st century. However, the magnitudes of changes in B2 scenario are on the lower side.

1. Introduction

It is hardly necessary to state that water is one of the most important minerals and vital for all life. Precipitation is the meteorological variable of the most importance since it conditions the availability of water at the surface. It has played an important role in the past, and in the future also it will play a central role in the well-being and development of our society. This most precious resource is sometimes scarce, sometimes plentiful, and always unevenly distributed in space and time.

Changes in the precipitation extreme events may require adaption and mitigation measures for proper water management. Recently, Alexander et al. [1] published the most up-to-date and comprehensive global picture of the observed trends in extremes in precipitation and found a general increase in the heavy precipitation indices. But the analysis suggests that compared to temperature changes, changes in precipitation extremes are less spatially coherent and at lower level of statistical significance. For the Indian region, their analysis shows the largest declining trends in the annual number of consecutive dry days. Earlier study over India [2] shows that most of the time series exhibit increasing trends in indices of precipitation extremes and that there are coherent regions with increases and decreases. Goswami et al. [3] have done the analysis of extreme rainfall events over Central India during the summer monsoon period, June-September, over the period 1951–2002 and shown significant rising trends in the frequency and magnitude of extreme rain events and significant decreasing trend in the frequency of moderate events. Their study also suggests no significant trend in seasonal mean rainfall, because the contribution from increasing heavy events is offset by decreasing moderate events.

The changes in precipitation extremes can occur related to global climate change as a result of anthropogenic greenhouse gas forcings. Increasingly reliable regional climate change projections are now available for many regions of the world due to advances in modelling and understanding of the physical processes of the climate system [4]. Atmosphere-Ocean General Circulation Models remain the primary source of regional information on the range of possible future climates. An increase in intense precipitation is projected under greenhouse warming conditions over large parts of the globe by most of the models [5, 6]. Most of the models show increase in extreme daily precipitation despite the decrease in mean precipitation. Much larger changes are expected in the recurrence frequency of precipitation extremes than in the magnitude of extremes [7–9].

Though monsoonal flows and tropical large-scale circulation weaken [10], enhanced moisture convergence in a warmer, moister atmosphere dominates over it and results into increased monsoon precipitation [11–17]. The warm SST experiments using RegCM3 show that the warming of SST over the Indian ocean enhanced the monsoon precipitation mainly over the south peninsular India, west peninsular India, and the Indian Ocean and reduced precipitation over northeast India [18]. In terms of short-duration rainfall using HADRM2 model, the future projections indicate decrease in the number of rainy days and an increase in the rainfall intensity as well as extreme rainfall magnitudes [19].

Frequency and intensity of cyclonic disturbances during the monsoon seasons and their likely changes in future using PRECIS have been examined by [20]. Their study indicates that the frequency of cyclonic disturbances is likely to decrease in future; however the systems may be more intense in global warming scenarios. The study also indicates that there is no significant change in the mean onset date of monsoon over Kerala in future scenarios, but there is relatively higher variability in the A2 scenario compared to the baseline. Also some of the characteristics of mean precipitation over the Indian region using PRECIS model scenarios have been examined by [21]. However, for the Indian region, the information about the precipitation extremes and its seasonal behaviour in the warming scenarios is scarcely available. Therefore, in the present paper an attempt has been made to study, in detail, the characteristic features of precipitation extremes and their seasonal behaviour using standardized indices as projected by state-of-art regional climate modeling system, known as PRECIS over the Indian region for the period 2071–2100.

2. Data and Method

2.1. Regional Climate Model Data. Simulations using PRECIS have been performed to generate the climate for present (1961–1990) and a future period (2071–2100) for two different socioeconomic scenarios both characterized by regionally focused development but with priority to economic issues in one (A2 scenario) and to environmental issues in the other (B2 scenario). Detailed description of these scenarios is available in [22] Special Report on Emission Scenarios (SRES). PRECIS has been configured for a domain extending from about 1.5°N to 38°N and 56°E to 103°E for horizontal resolution of $0.44^\circ \times 0.44^\circ$ and 19 layers in the vertical. PRECIS is forced at its lateral boundaries by a high-resolution GCM (150×150 km) called HadAM3H in "time slice" experiments. HadAM3H is an atmosphere-only model which has been derived from the atmospheric component of HadCM3 [23, 24], the Hadley Centre's state of the art coupled model which has a horizontal resolution of 3.75° latitude by 2.5° longitude. A complete description of PRECIS is provided by [25]. An important aspect of PRECIS simulations is the role of sulphur cycle. But from a general comparison of the simulations performed with and without sulphur cycle switched on in the regional model, it appears that there is no marked change in the simulations either in terms of rainfall or in terms of surface air temperature [21]. It may be noted that, as the driving GCM already has the sulphate aerosols included, the Lateral Boundary Conditions do contain the associated large-scale signals. Therefore, the results suggest that the regional sulphur cycle as considered by the model has no major impact on the scenarios derived. In the present study, precipitation extremes are investigated to see their future scenarios using PRECIS daily precipitation data for the baseline (1961–1990) and for the A2 and B2 scenarios (2071–2100) with sulphur cycle.

2.2. Methodology. The joint World Meteorological Organization Commission for Climatology (CCI), World Climate Research Programme (WCRP) project on climate variability and Predictability (CLIVAR) Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) coordinate efforts to and developed a suite of climate change indices which are primarily focus on indices which derived from daily precipitation data and user-friendly software package "RClimdex" (available at http://cccma.seos.uvic.ca/ETCCDMI/) [26]. Precipitation extreme indices as listed in Table 1 are calculated, with this software at each grid using RCM data.

3. Results and Discussions

Comparing with gridded data based on the CRU data sets, Rupa Kumar et al. [21] have shown that mean seasonal precipitation patterns are well captured by PRECIS in terms of annual cycle as well as spatial patterns. Their analysis indicates that model's baseline simulations provide an adequate representation of present-day conditions with rainfall maximum over west coast of India and the rain-shadow region in the southern peninsula. Revadekar [27] has seen that PRECIS is also able to capture annual cycle and spatial patterns of precipitation extremes over entire land mass covering India by comparing with observed network of 146 stations.

In present paper an attempt is made to evaluate various aspects of future projections of precipitation extremes over India, as projected by PRECIS towards the end of the 21st century, using standardized indices. To remove quantitative biases, changes in future precipitation are presented in terms of gradient of present day precipitation.

3.1. Annual Cycles. Increase in monsoon precipitation is seen through the annual cycle based on monthly mean all-India

Table 1: List of Indices used in the study.

Index	Description	Definition
R10 mm	Frequencies in days	Number of days with precipitation > 10 mm
R20 mm	Frequencies in days	Number of days with precipitation > 20 mm
R99 p	Frequencies in days	Precipitation due to heavy precipitation event exceeding 95p
R99 p	Frequencies in days	precipitation due to heavy precipitation event exceeding 99p
RX1day	Intensity in mm	One-day maximum precipitation
RX5day	Intensity in mm	Five-day maximum precipitation
CWD	Longest spell duration in days	Continuous wet days when precipitation > 1 mm
SDII	Daily intensity	Simple Daily Intensity in mm/rainy days

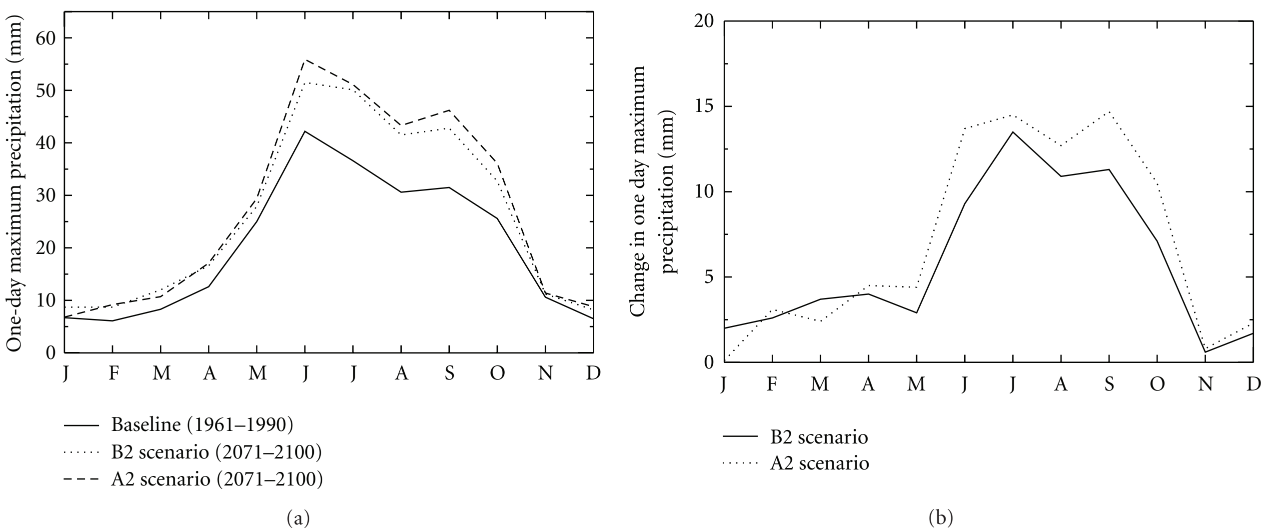


Figure 1: Monthly mean all-India one-day maximum precipitation in mm (RX1day, (a)) as simulated by baseline (1961–1990), A2 and B2 scenarios (2071–2100) and changes in one day maximum precipitation in A2 and B2 scenarios with respect to baseline (b).

one-day maximum precipitation (Figure 1). Seasonal cycles are well captured with the dominance of summer monsoon (JJAS) season over the Indian region with very high values of one-day maximum precipitation throughout the season. A2 and B2 scenarios show similar patterns of annual cycles indicating no major changes in seasonality.

Both A2 and B2 scenarios show increase in one-day maximum precipitation towards the end of the 21st century. However their magnitudes differ from month to month. Least changes in one-day maximum precipitation are seen in winter season, and dominance of summer monsoon season is likely to be enhanced over the Indian region.

In general, changes in one-day maximum precipitation are higher in A2 scenarios than in B2 scenarios. However, monsoon months show high magnitude increment in one-day maximum precipitation than in the remaining months.

Five-day maximum precipitation also represents similar features (not shown). Thus, strong monsoon activities are likely to occur over the Indian region towards the end of the 21st century in a global warming scenario.

3.2. Seasonal Spatial Patterns. Extremes are computed at each grid point of PRECIS domain over South Asia, for all the seasons: DJF, MAM, JJAS, and ON, for all the thirty years of baseline (1961–1990), A2 and B2 scenarios (2071–2100). Changes in 30-year average values of indices of extremes are presented in terms of their spatial patterns.

3.2.1. Intensity Indices. Figure 2 shows the changes in A2 scenarios of intensity of extremes precipitation, in terms of the one-day maximum precipitation, towards the end of the 21st century. There is a general increase all over India in heavy rainfall activities during summer monsoon and post-monsoon. Spatial patterns of changes in one-day maximum precipitation show higher magnitude changes in summer monsoon season. Less conspicuous changes are seen in the DJF and MAM seasons; however during the MAM northeast regions of India show strong rainfall activities. These may be related to enhanced pre-monsoon thunderstorm activities over the region.

During summer monsoon there is a marked increase over an extensive area of about 40–80 mm, covering the Western Ghats and northwestern peninsular India including Maharashtra and adjoining parts of Andhra Pradesh, Madhya Pradesh, and Karnataka. Northeast region and parts of Himachal Pradesh and Uttarakhand also show increase

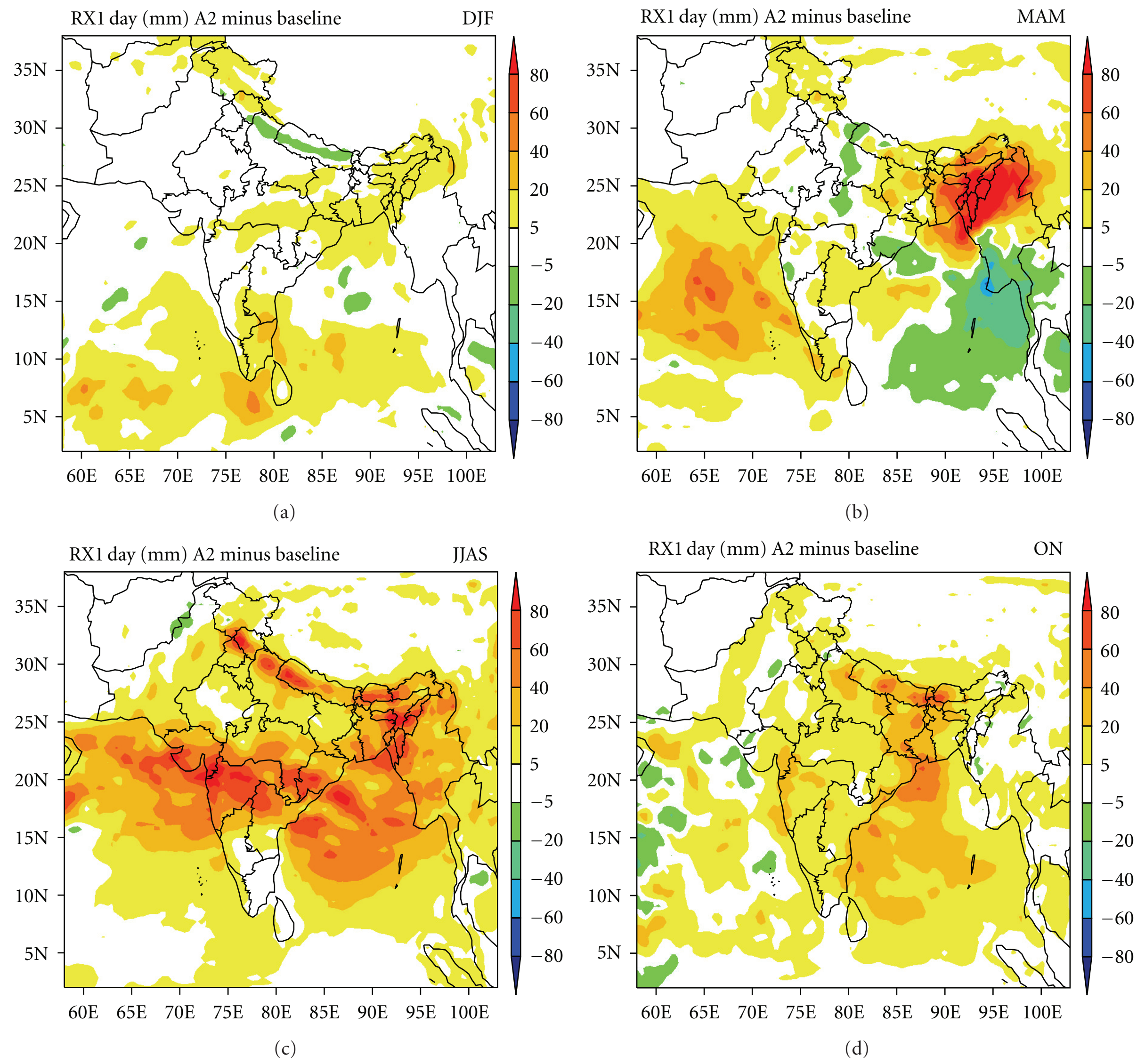


Figure 2: Spatial patterns of changes in seasonal one-day maximum precipitation in mm, RX1day {A2 (2071–2100) minus baseline (1961–1990)} in DJF (a); MAM (b); JJAS (c); ON (d).

in one-day maximum precipitation. During post-monsoon season also, almost all land areas show increase in one-day maximum precipitation. However, the changes in post-monsoon season have relatively lower magnitudes than those of summer monsoon season.

Similar spatial patterns are seen for seasonal changes in five-day maximum precipitation. Thus, the enhanced heavy rainfall activities seen in summer monsoon and indicated by the all-India mean annual cycles are associated with widespread projected increases in both one-day and five-day maximum precipitation over the Indian landmass.

3.2.2. Frequency Indices. Seasonal frequencies of heavy rainfall activities are computed by counting the days in the season for which the daily rainfall exceeds 10 mm (R10 mm). R10 mm values are computed at each grid point for the baseline (1961–1990) as well as for A2 (2071–2100) scenarios. To understand the changes in the frequencies of heavy rainfall activities, the differences in the frequencies between A2 scenario and the baseline are presented in Figure 3.

Frequency indices of heavy precipitation (R10 mm) also show higher changes during the summer monsoon season. Rest of the year shows no marked changes in R10 mm, except over northeast region during the MAM season which shows increase of more than 7 days in R10 mm.

Regions of higher magnitude changes in frequency are the same as those of the regions of higher magnitude changes in intensity indices. R10 mm also shows that there is a marked increase over an extensive area covering the Western Ghats and northwestern peninsular India including

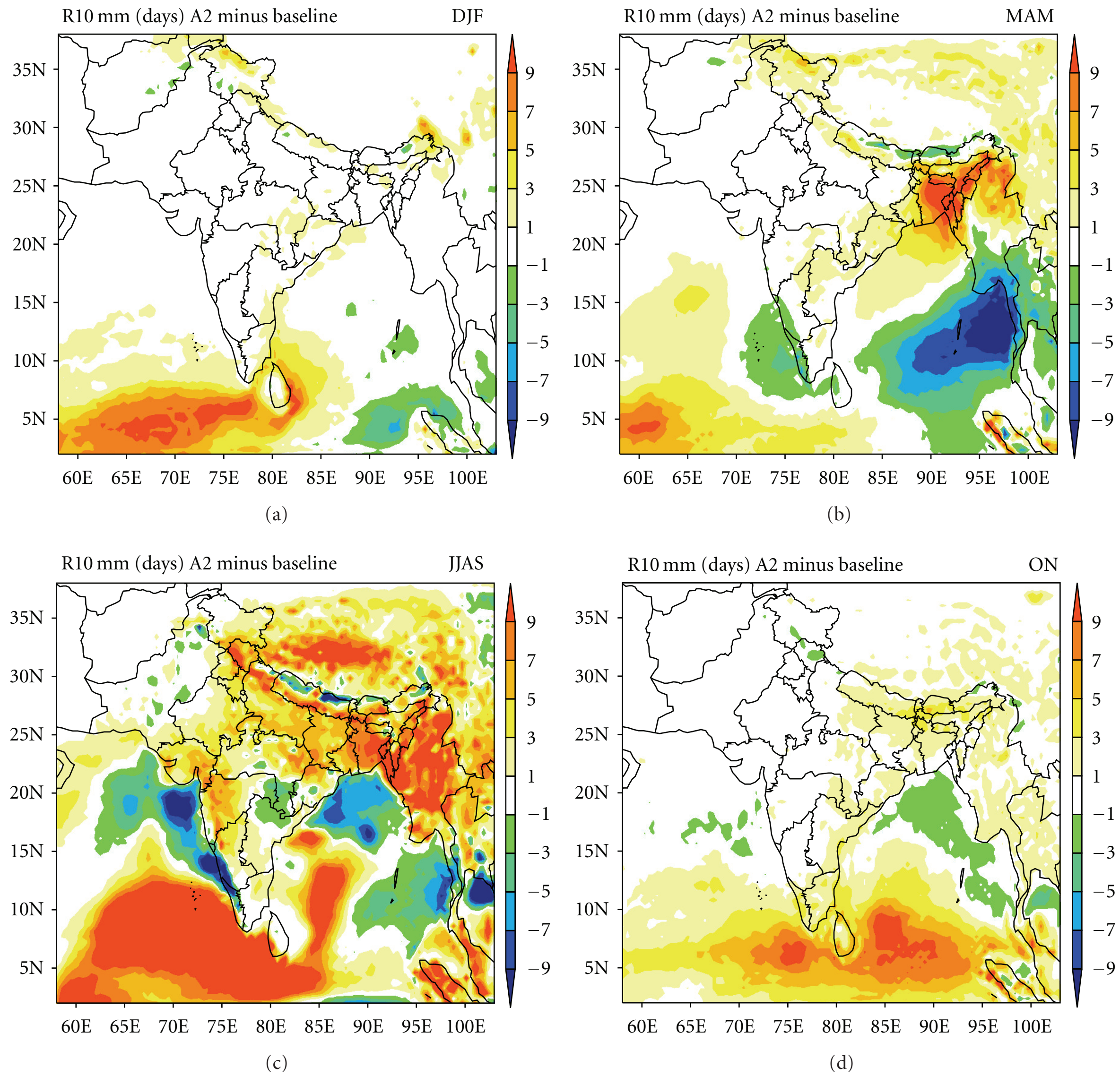


Figure 3: Spatial patterns of changes in seasonal count of days when precipitation exceeding 10 mm, R10 mm {A2 (2071–2100)minus baseline (1961–1990)} in DJF (a); MAM (b); JJAS (c); ON (d).

Maharashtra and adjoining parts of Andhra Pradesh, Madhya Pradesh, and Karnataka, Northeast region and parts of Himachal Pradesh and Uttarakhand.

Coastal Karnataka is an exceptional region where the frequencies of heavy precipitation events are likely to reduce in the future.

Unlike the wide spread increase in one-day maximum precipitation (Figure 2) during the post-monsoon season (ON), there are no perceptible projected changes in the frequencies (Figure 3) of heavy precipitation events.

3.3. Space-Time Distribution. Hovmoller plots can be particularly useful for data visualizations to detect variations over time and space simultaneously. For this purpose, for each calendar day, 30-year means have been computed for each grid point for the baseline (1961–1990) as well as A2 and B2 scenarios (2071–2100).

Hovmoller plots for space-time distribution of daily precipitation for baseline (1961–1990), A2 scenario (2071–2100) and the change in precipitation in A2 scenario with reference to baseline (A2 minus baseline), averaged over the longitudinal range 70–80E, are presented in Figure 4. The figure essentially presents daily precipitation over India in terms of time-latitude variation.

The plot for baseline (1961–1990) clearly shows summer monsoon dominance. The phases of onset, progress, and withdrawal with clear south-to-north and reverse progressions are seen in the figure. The A2 scenario (2071–2100) also shows similar features indicating that the projected future seasonal characteristics of summer monsoon are likely to remain the same towards the end of the 21st century.

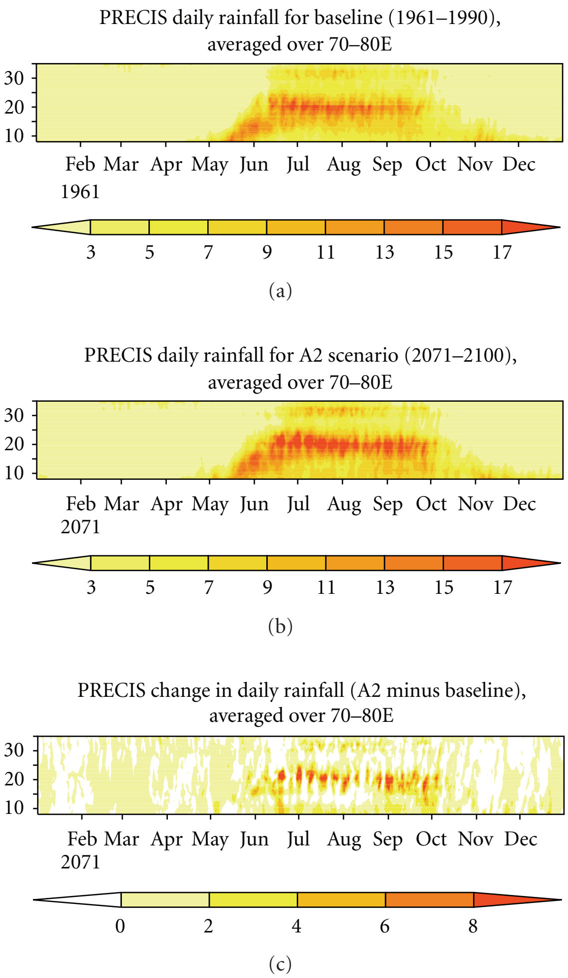


Figure 4: Hovmoller plot for space-time distribution of daily precipitation for baseline (1961–1990, (a)), A2 scenarios (2071–2100, (b)) and change in precipitation in A2 scenarios with respect to baseline (A2 minus baseline, (c)), averaged over the region 70–80°E.

However, there are marked increases in the daily precipitation by about 6–8 mm/day during the summer monsoon season in the future projections. Also, an increase in precipitation is seen throughout the season not continuously but in periodic pulses, indicating possible changes in active-break cycles within the season.

It is well known that the rainfall distribution over India varies considerably from day to day. Over major parts, rain occurs in spells under the influence of favourable circulation conditions. This intermittent behavior of rainfall is associated with a hierarchy of quasiperiods, namely, 3–7 days, 10–20 days, and 30–60 days. The Hovmoller plots suggest the dominance of faster mode on the projected monsoons. Several earlier studies have shown the direct relationship of faster mode intraseasonal oscillation and Indian monsoon strength [28–31].

3.4. Summer Monsoon Features. It is well known that, each year the summer monsoon (JJAS) brings large amounts of rain for most of the country, while other parts of the country can experience serious drought. When the monsoon systems are arriving over the country, rainfall distribution is dependent on the geographical conditions. Indian summer monsoon rainfall plays dominant role in agricultural production, economy, and human lives [32–34]. Keeping in mind the importance of summer monsoon precipitation (JJAS) in the Indian context and also higher changes seen in one-day and five-day maximum precipitation from annual cycles and seasonal spatial patterns in previous sections during the season, an attempt is made in this section to see thorough changes in summer monsoon precipitation extremes towards the end of the 21st century.

3.4.1. Probability Distribution Function. Probability distribution functions (PDFs) are calculated for indices of precipitation extremes for baseline (1961–1990), A2 and B2 scenarios (2071–2100) using indices of each year at all grids to understand the changes which are likely to occur in the future over the Indian land mass.

Figure 5 shows the PDFs for (1) daily intensity (SDII, mm/rainy days); (2) five-day maximum precipitation (RX5 day, mm); (3) count of days when rainfall exceeds 20 mm (R20 mm, days) and (4) maximum spell of continuous wet days (CWD, days) for baseline, A2 and B2 scenarios.

All the PDFs show positive shift in precipitation extremes in both A2 and B2 scenarios indicating reduction in low-precipitation extremes and increase in high-precipitation extremes. Changes in B2 scenarios are low compared to changes in A2 scenarios. It can also be seen from the figure that the probability of mean value of precipitation extremes has been reduced in both A2 and B2 scenarios with slightly more reduction in A2 scenarios. Higher changes are seen for SDII and RX5day.

Other indices of precipitation extremes during summer monsoon season like RX1day, R10 mm, R30 mm, and CDD also represent similar features (not shown). In general, there is an indication towards the wetter climate, with notable increases in summer monsoon precipitation extremes.

3.4.2. Regional Extremes. Though most parts of India receive the bulk of annual precipitation during period of June to September, hills and mountain ranges display striking variations in precipitation. The extreme northern part of India, which is cut off from the southwest monsoon current by orographic barrier, receives most of its precipitation in the form of rain or snow during the winter months from eastward moving extratropical systems known as western disturbances. These disturbances are the main sources of winter precipitation over the plains and adjoining mountain ranges of northwest India. The regions which receive the largest amount of summer monsoon precipitation are along the west coast in India and the states of Assam and West Bengal in northeast India. In these regions also, orography plays an important role. Along the west coast, the orientation of the western ghats from north to south plays an important role. In this context, it is appropriate to study the statewise

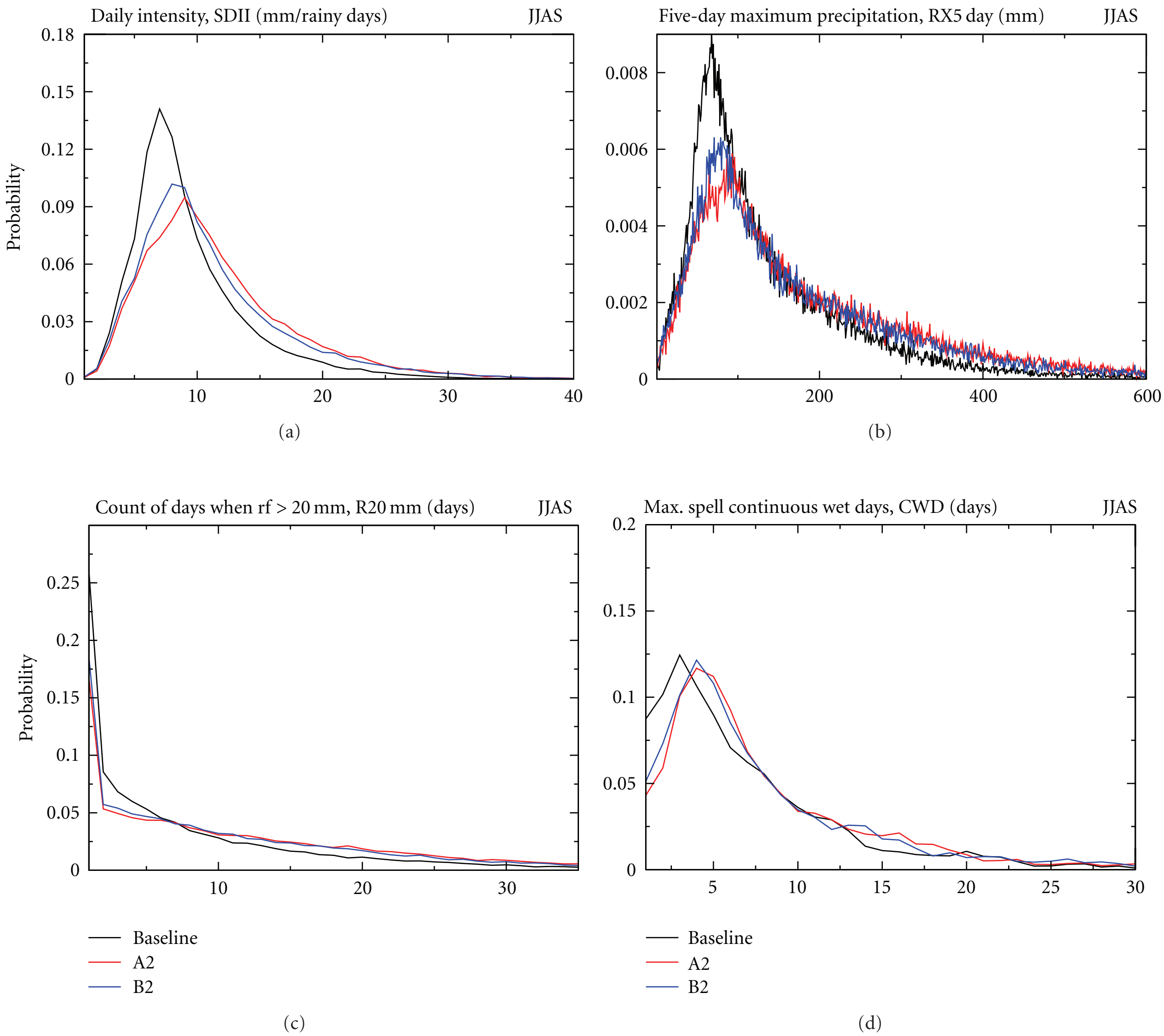
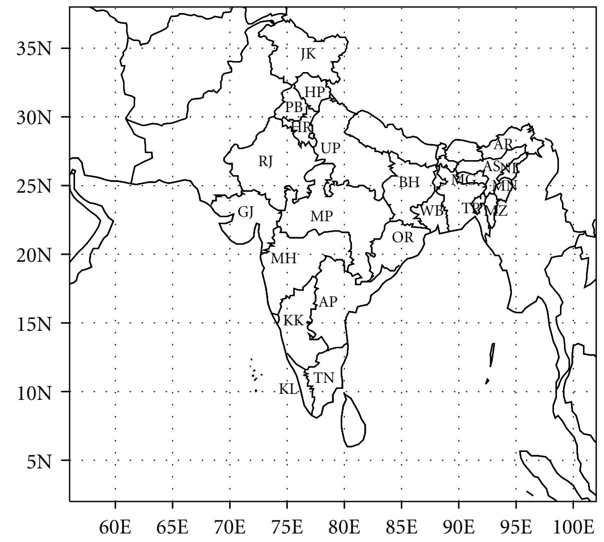


Figure 5: Probability distribution function of daily intensity, SDII ((a), mm/rainy days); five-day maximum precipitation, RX5day ((b), mm); count of days when rf > 20 mm, R20 mm ((c), days) and maximum spell of continuous wet days, CWD, ((d), days). For baseline (1961–1990), A2 and B2 scenarios (2071–2100) during Indian summer monsoon season (JJAS).

changes in precipitation extremes. For this purpose, average values of grids covering the state land mass are considered as representative value of that state. Location of the states is as shown in Figure 6.

Mean Precipitation. Statewise changes in seasonal precipitation in A2 and B2 scenarios in terms of percentage changes from baseline, presented in Figure 7, show positive changes in all states except three states from less precipitation zone. Also the magnitudes of negative changes are very small compared to the magnitudes of positive changes. Magnitudes of changes in A2 scenarios are higher than those in the B2 scenarios for most of the states. Very high changes in precipitation exceeding thirty percent of baseline precipitations are from the states covering northeast regions of the country.

Precipitation Extremes. Indices of precipitation extremes also show similar pattern of statewise changes as seen in mean precipitation (Figure 8). However notably no state is showing negative change for all indices of extremes except for the five-day maximum precipitation Figure 8(b) with two states which show negative change with very small magnitude for B2 scenario. State of Kerala (last bar of each chart) shows very high changes in frequency as well as rain amount received from heavy and very heavy precipitation events. Also spell duration of continuous heavy rainfall days is likely to increase substantially over this state. This is the state at the tip of



JK: Jammu
PB: Punjab
HP: Himachal Pradesh
HR: Haryana
UP: Uttar Pradesh
BH: Bihar
WB: West Bengal
AS: Assam
MG: Meghalaya
TP: Tripura
AR: Arunachal
NL: Nagaland
MN: Manipur
MZ: Mizoram
OR: Orissa
MP: Madhya Pradesh
RJ: Rajasthan
GJ: Gujarat
MH: Maharashtra
KK: Karnataka
AP: Andhra Pradesh
TN: Tamil Nadu
KL: Kerala

Figure 6: Geographical location of states of India.

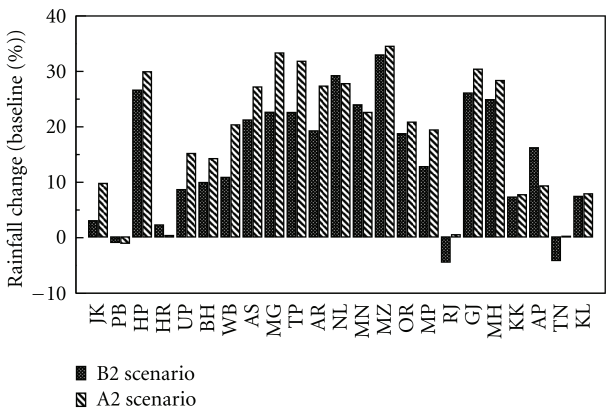


Figure 7: Statewise changes in seasonal precipitation in A2 and B2 scenarios (2071–2100) in terms of percentage of baseline (1961–1990).

Indian peninsula where the onset of monsoon first takes place.

4. Conclusions

The detection of possible changes in extreme climate events, in terms of the frequency, intensity as well as duration assumes profound importance on the local, regional, and national scales, due to the associated critical socioeconomic consequences. Changes in the frequency as well as intensity of extreme climate events would have profound impacts on human society, infrastructure, natural resources, and ecosystem. Therefore, extreme climate and weather events are increasingly being recognized as the key aspects of climate change assessment. With the growing concern of the regional manifestations of global warming, one of the important aspects of climate change research is an objective characterization of precipitation extremes and future scenarios. Models calibrated with the backdrop of the current climate can be used to project the future changes due to natural climate fluctuations as well as anthropogenic forcings such as greenhouse gas increase. With this background, a comprehensive analysis has been done in the present paper to study in detail characteristic features of precipitation extremes and its seasonal behavior using standardized indices on PRECIS simulations over the Indian region for the period 2071–2100. Following are some noteworthy conclusions,

(i) Model simulations under scenarios of increasing greenhouse gas concentration and sulphate aerosols indicate marked increase in precipitation towards the end of the 21st century.

(ii) PRECIS simulations under both A2 and B2 scenarios indicate increase in frequency of heavy precipitation events and enhancement in their intensity towards the end of the 21st century.

(iii) Precipitation is expected to increase in entire calendar year; however the changes in daily precipitation and the extremes during summer monsoon (JJAS) season are prominent than during the rest of the year.

(iv) Both A2 and B2 scenarios show similar patterns of projected changes in the precipitation extremes towards the end of the 21st century. However, B2 scenario shows slight lower magnitudes of the projected changes than those of A2 scenarios.

(v) The large spatial variability of future precipitation extremes is a clear evidence of the importance of using regional scale climate models to improve our understanding of these issues.

Thus, while analysis on future projections of precipitation extremes indicates broad-scale regional changes through the seasonal and regional indices, it is necessary to examine the extremes in detail and also to study the factors affecting the enhancement of extremes. Also, the PRECIS-based scenarios in this paper are presented/interpreted in terms of qualitative aspects, indicating the expected range of changes in precipitation extremes. Quantitative estimates have large uncertainties associated with them, which need to be assessed using more ensembles of the model simulations.

Acknowledgments

This work is part of a Joint Indo-UK collaborative programme on climate change impacts in India. The authors are grateful to the Department for Environment, Food and Rural Affairs (DEFRA), Government of the United Kingdom, for sponsoring this project and the Ministry of Environment

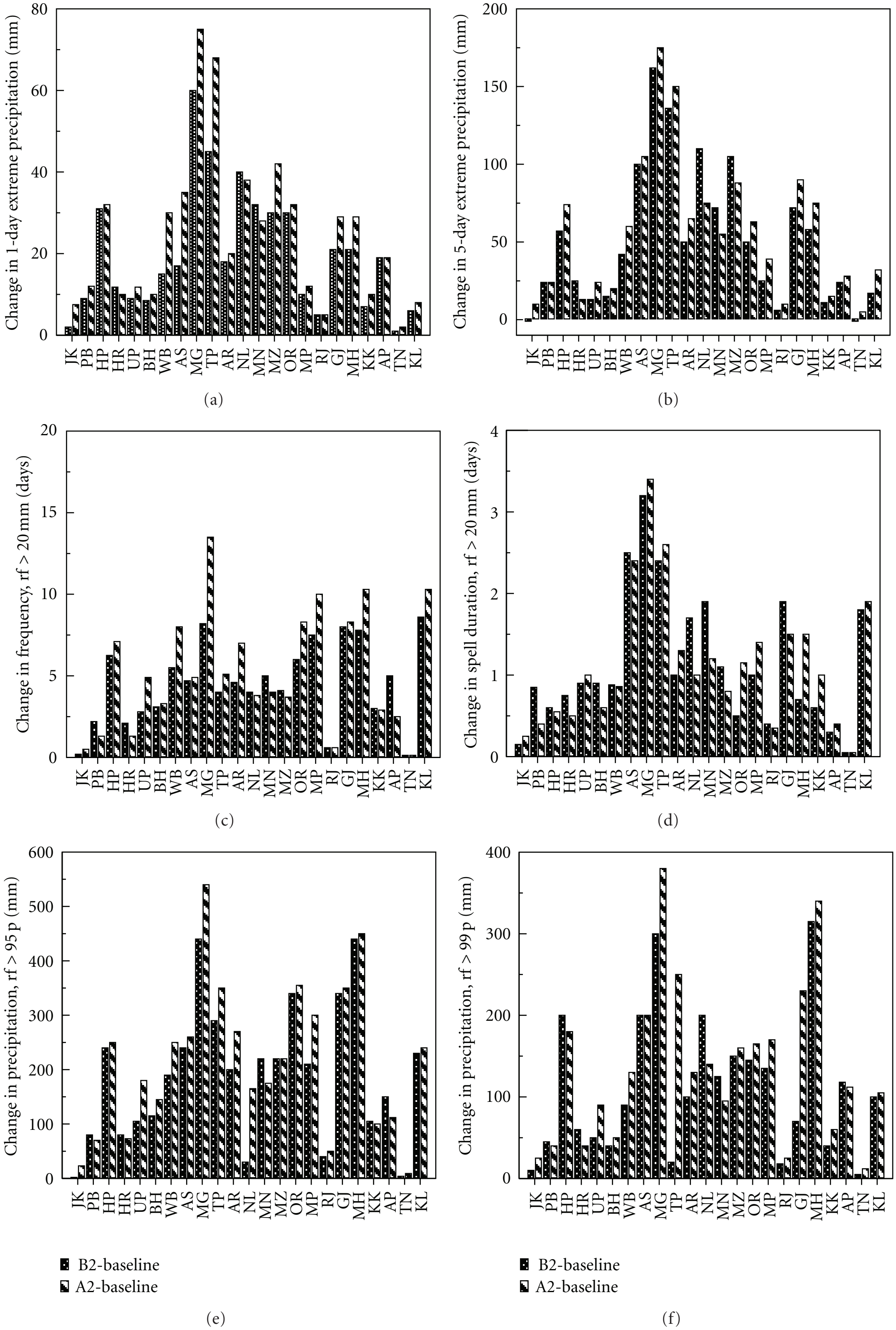


Figure 8: Statewise changes in one-day maximum precipitation (a) and five-day maximum precipitation (b); count of heavy rainfall days when rainfall exceeds 20 mm (c) and spell duration of continuous heavy rainfall days (d) and heavy precipitation amount when rainfall exceeds 95th percentile, (e) and very heavy precipitation amount when rainfall exceeds 99th percentile (f) in A2 and B2 scenarios (2071–2100) with respect to baseline (1961–1990).

and Forest (MoEF), Government of India, for coordinating its implementation. The project team is grateful to the Hadley Centre for Climate Prediction and Research, UK Meteorological Office, for making the regional models and their data products available for this study.

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