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Sub-Basin Scale Characterizations of the Changes of the Future Rainfall Over the Ganges River Basin Using High Resolution Regional Climate Model

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Abstract: ***Global warming affects the seasonal rainfall variation and changes extreme rainfall events, in terms of frequency and intensity have an impact on the local, regional and global scales. An attempt has been made in this study to define the rainfall features of Ganges basin under moderate climate change scenario. The river basin has diversified climatic patterns. Ganges river basin is divided into 14 major sub basins. However, impact of climate change over Ganges is observed using Hadley Center's regional Climate model, PRECIS (Providing Regional Climates for Impact Studies). PRECIS simulation was carried out corresponding to SRES A1B scenario for a time period of 1971-2099. PRECIS generated rainfall shows deviation from observed rainfall therefore simulated rainfall needs to be corrected with respect to observed rainfall for impact studies. In these particular study PRECIS generated rainfall time series is bias corrected with respect to rainfall data of Indian Meteorological Department. The climate projections are examined over three time slices, viz. near (2020s, i.e. 2011–2040), farther (2050s, i.e. 2041–2070) and transient (2080s, i.e. 2071–2099). Analysis indicates that monsoon rainfall increases 0.01% at 2020's, 5.5% at 2050's and 7.3% at 2080's. Probability of rainfall extreme over Ganges basin such as maximum 1 day rainfall, count of consecutive rainfall days shows increasing trend, on the other hand number of rainfall event (>20 mm) on monsoon season shows decreasing trend.***

Keywords: Bias correction, consecutive rainfall days, Global warming, monsoon regional climate model and rainfall extreme

1. Introduction

Precipitation is an important meteorological variable as it ensures the availability of fresh 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. Precipitation extreme events are projected to increase, particularly in tropical and high latitude areas that experience increases in mean precipitation. Even in areas where mean precipitation decreases (most subtropical and mid-latitude regions), precipitation intensity is projected to increase but there would be longer periods between rainfall events. Alexander et al. [7] published a comprehensive global picture of annual trends in extreme rainfall and found increase in the heavy precipitation indices. For the Indian region their analysis shows the declining trends in the annual number of consecutive dry days. Earlier study over India by Roy et al. [9] shows that most of the time series exhibit increasing trends in indices of precipitation extremes. Goswami et al. [8] 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. Due to advances in modelling and understanding of the physical processes of the climate system, atmosphere- Ocean General Circulation models remains the primary source of regional information on the range of possible future climates [14]. According to Kharin et al. [12] and Wehner et al. [11] an increase in intense precipitation is projected under greenhouse warming conditions over large parts of the globe by most of the models. Study of Singhs et al. [5] have performed warm SST experiments using RegCM3 their study shows 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. Kumar et al. [4] has Simulated projections for summer monsoon climate over India by a high-resolution regional climate model (PRECIS). His study indicates 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 (A1B scenario). Also, the rainy days are projected to be less frequent and more intense over central India. Study of Revadekar et al. [3] reveals that PRECIS simulation under scenarios of increasing greenhouse gas concentration (A2 and B2 scenario) and sulphate aerosols indicate increase in precipitation towards the end of 21st century (2071-2100).

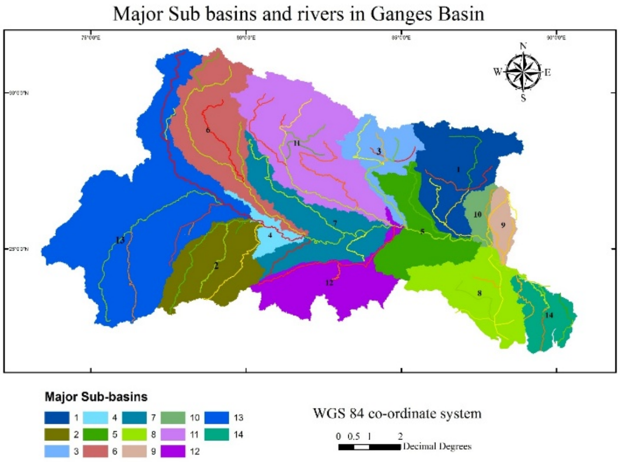

Figure 1: Major River Systems of Ganges river basin.

Their study shows that daily precipitation and the precipitation extremes during summer monsoon (June through September) are prominent. PRECIS simulation under both A2 and B2 scenarios indicate increase in frequency of heavy precipitation events and also enhancement of their intensity. Both A2 and B2 scenarios similar pattern of projected changes in precipitation extremes, however the magnitudes of changes of B2 scenario are on the lower side. Rao et al. [1] has performed projected changes in mean and extreme precipitation indices over India using PRECIS. In his study projected changes in various precipitation extremes show a large regional variability. Total rainfall on very heavy rainy days (R95p) is projected to increase by around 40-50% over the central parts of the country. The number of rainy days > 10 mm (R10) may increase by 10-20% over west coast, east central India and northeastern parts while over northwest and rain shadow region they may increase by 40-50%. The consecutive dry days (CDD) may decrease by 10-20% over Indo- Gangetic plain, however over west coast there may not be any significant change. The CDDs are projected to rise by 10-20% over west central and peninsular India. The precipitation per wet day (SDII) may be more intense by 10-40% over the entire land mass.

2. Data and Methodology

2.1 Available historical observed data at Ganges river basin

To anticipate the rainfall change over Ganges Basin both projected and observed daily time series data are used. For the purpose of rainfall analysis at present, rainfall condition over Ganges basin meteorological data are collected from Indian Meteorological Department (IMD) and Bangladesh Meteorological Department (BMD). IMD gridded data have been presented rainfall at a 0.5 degree resolution over Ganges basin. BMD data are collected from 9 meteorological stations located in the southwest region of Bangladesh.

2.2 Regional climate model data

PRECIS is used for dynamic downscaling. Simulations using PRECIS have been performed to generate a daily time series (1970-2100) using AR4 moderate emission scenario (A1B scenario) scenario. Detailed description of these scenarios is available in Davis et al. (2000).

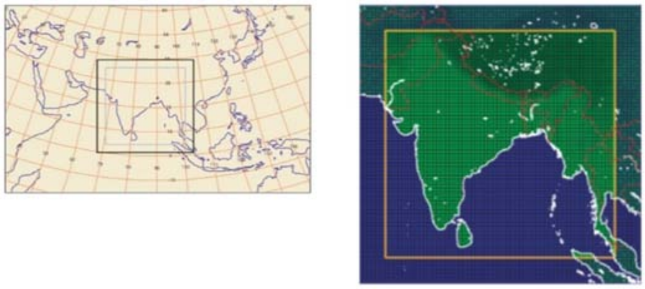

Figure 2: Domain used for PRECIS simulation.

PRECIS has been forced at its lateral boundaries by 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 (Gordon et al. [14] and Pope et al. [15]), 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 Jones et al. [10]. An important aspect of PRECIS simulations is the role of sulphur cycle. In the present study, precipitation extremes are investigated to see their future scenarios using PRECIS daily precipitation data for the baseline (1971–2000) and for the A1B scenario (2011–2100) with sulphur cycle .Simulation is carried out using lateral boundary data from HadCM3 under A1B scenario. Daily time series data are generated at 25 km x 25 km resolution (Figure 2).

2.3 Methodology

To catch the rainfall variability of Ganges basin in the changing climate it is necessary to divide the river basin into fourteen smaller sub catchments (**Figure 1**). Sub catchments and their respective regions are presented in **Table 1**

Table 1: Catchments and their respective regions

Catchment	Name of the region
Catchment 1	Part of Nepal and Bihar
Catchment 2	Part of Madhya pradesh
Catchment 3	Part of Uttar pradesh and Nepal
Catchment 4	Part of Uttar pradesh
catchment 5	Part of Bihar
Catchment 6	Part of Uttaranchal and Uttar pradesh
Catchment 7	Uttar pradesh and madhya pradesh
catchmnt 8	Part of west bengal
Catchment 9	Part of west bengal
Catchment 10	Part of Bihar
Catchment 11	Part of Nepal and Uttar pradesh
Catchment 12	Part of Madhya pradesh, Uttar pradesh, Jharkhand, Chhattisgarh
Catchment 13	Rajasthan, Part of Madhya pradesh
Catchment 14	Southwest region of Bangladesh

Seasonal precipitation intensity is calculated in each sub basins (**section 5**). Sub basins of Ganges are established by catchment delineation with SRTM (Shuttle radar topographic mission [18]) 90m Digital Elevation Data. Spatial variation was calculated for monsoon rainfall intensity and precipitation extremes specified in **section 7**.

3. Bias Correction

Climate change results (rainfall, temperature) are often used in Hydrological models to see the possible changes in surface runoff, ground water recharge, snowmelt runoff and fresh water storage. Rainfall simulated by RCM shows slightly over or less rainfall at base period in different seasons, such as downscaled data normally over predicts rainfall intensity at dry season. Using the rainfall data directly for hydrological model simulation will give unrealistic results. Hence, to achieve correct and realistic results, it is necessary to alleviate the biases from the climate model output by comparing with the observed data. There are various ways of bias corrections can be conducted. Considering the complexity and performances of different methods, the most simplified method, Delta change approach has been adopted in this study which is suggested by Wilby et al. [13]. The percentage bias of monthly mean rainfall between observed and simulated data is calculated at base period for each month. Then, percentage bias is applied to simulated data in future period to achieve bias corrected rainfall. This approaches are presented by the following two simple equations (Eqn. 1 and 2)-

$$Monthly\ Bias = (observed\ mean\ monthly\ rainfall - simulated\ mean\ monthly\ rainfall)/(observed\ mean\ monthly\ rainfall) * 100\% \quad (1)$$

$$Corrected\ daily\ rainfall = Simulated\ daily\ rainfall * (1 + Monthly\ Bias/100) \quad (2)$$

To perform bias correction it is assumed that one specific rainfall station influences gridded downscaled rainfall station within 27.5 km circumference radius. PRECIS data that falls within an influenced radius are bias corrected for the influential gridded IMD rainfall time series. Normally, one influential IMD gridded time series influences nearside nine different PRECIS nodes. The nearest IMD node will also influence nine different PRECIS nodes; therefore for two adjacent IMD nodes have three influential PRECIS node in common. But bias correction is performed only for one IMD node. Hence, double bias correction for different IMD node is avoided. Monthly monsoon rainfall at different seasons such as dry season, pre monsoon, monsoon and post monsoon season are calculated using bias corrected rainfall data.

4. Validation of Bias Corrected Rainfall

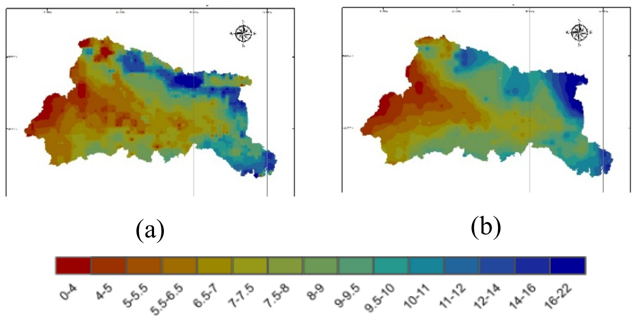

Figure 3: Validation Monthly monsoon (JJAS) rainfall at base period

Spatial analysis of monsoon rainfall shows similarity both in observed and modeled rainfall (**Figure 3**) at the base period. Therefore bias correction shows excellent performance over the Ganges basin except in the upper right corner of the Ganges basin.

5. Change in Seasonal Mean Precipitation

Simulated percentage changes in seasonal precipitation (Dry, pre monsoon, monsoon and post monsoon season) in the 2020s, 2050s and 2080s with respect to base period (1971-2000) are shown in **Figure 4** to **Figure** 7.

Rainfall intensity during dry season and pre monsoon season are observed to decrease (**Figure 4** and Figure 5 respectively). Whereas **Figure 6** reveals rainfall intensity will increase in catchment 1, catchment 2, catchment 6, catchment 8, catchment 11, catchment 14.

In the post monsoon season rainfall intensity will be decreased in most of the catchments at 2020's and 2050's, however precipitation intensity shows the increment at 2080's.

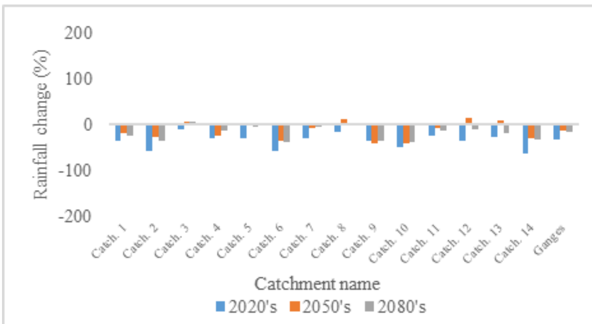

Figure 4: Dry season (DJF) rainfall change in Ganges Basin catchment.

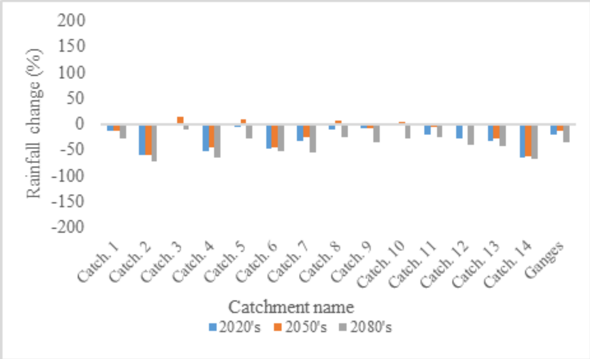

Figure 5: Pre-monsoon (MAM) rainfall change in Ganges Basin catchment.

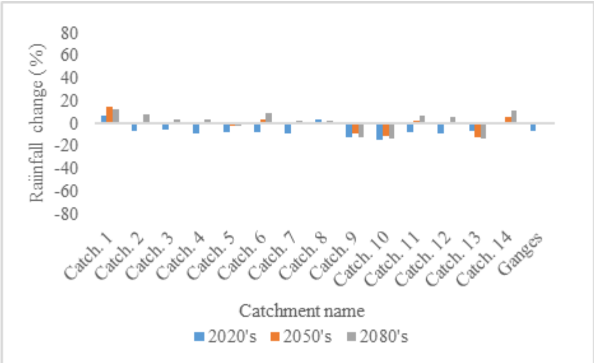

Figure 6: Monsoon (JJAS) rainfall change in Ganges Basin catchment.

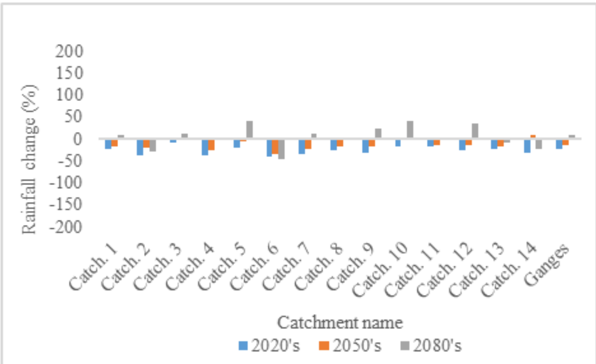

Figure 7: Post- monsoon (ON) rainfall change in Ganges Basin catchment.

6. Spatial Pattern of Monsoon Rainfall

Spatial plot of average monsoon rainfall for base period (1970's) and projection period (2020's, 2050's and 2080's) is shown in **Figure 8**.

Analysis result shows 17%, 10%, 12%, 8% and 15% rise of precipitation intensity in catchment 1, catchment 2, catchment 6, catchment 11 and catchment 14 respectively, towards the end of 21^{th} century. These catchment falls into Madhya Pradesh, Southwest region of Bangladesh and in Nepal. Rest of the catchments indicate fall of precipitation intensity, which indicates a drier climate in overall Ganges basin.

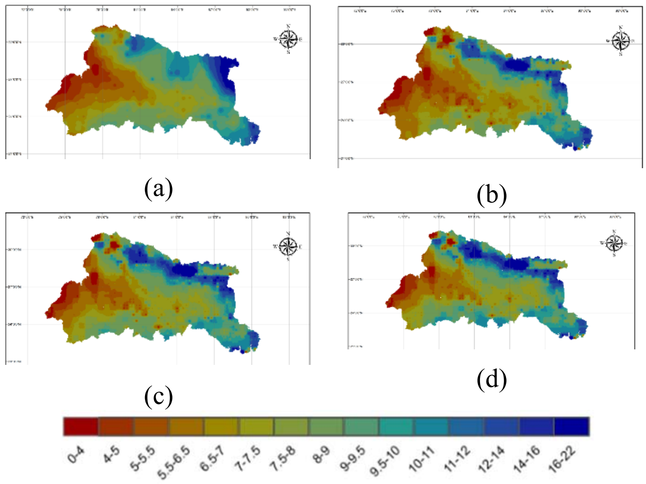

Figure 8: Spatial plot of monsoon (JJAS) rainfall intensity at base (a), 2020's (b), 2050's (c) and 2080's (d).

7. Spatial Change in Extreme Precipitation Event

Spatial plot of Maximum 1 day precipitation (RX1), Number of days with precipitation > 20 mm (R20) gives an idea to see the through change of summer monsoon rainfall extremes towards the end of 21^{st} century.

An importance feature during the monsoon of Ganges basin is the occurrence of heavy rainfall, (characterized by RX1) is associated with meteorological situation of the such as orographic lifting of moisture laden winds, heavy rain for periods of the day with cyclonic storm and short period heavy rainfall with thunderstorms.

Spatial map of RX1 in **Figure 9** shows, in the near future, i.e. 2020's and 2050's, maximum 1 day rainfall decreases in catchment 4 and catchment 7. However towards the end of 21th century it will increase in the most part of Ganges basin.

The occurrence of exceptionally heavy rainfall events (regarded as R20) are associated with flash floods in many areas, study shows extreme rainfall events increases in some parts of Nepal and Southwest region of Bangladesh (**Figure 10**). On the other hand, R20 decreases significantly in central and western portion of Ganges Basin.

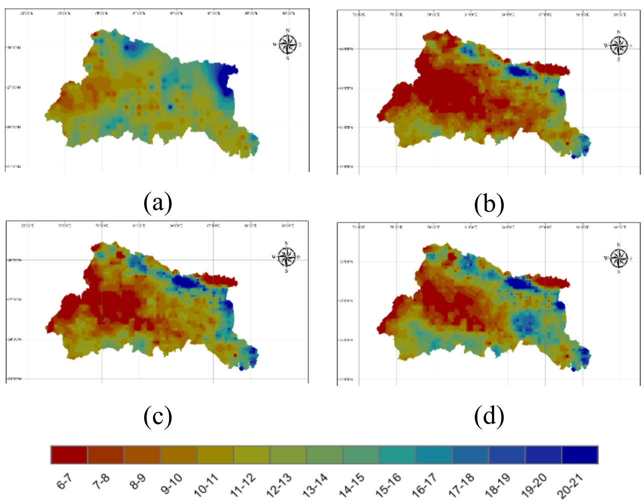

Figure 9: Spatial plot of Maximum 1 day precipitation (RX1) at base (a), 2020's (b), 2050's (c) and 2080's (d) during monsoon (JJAS).

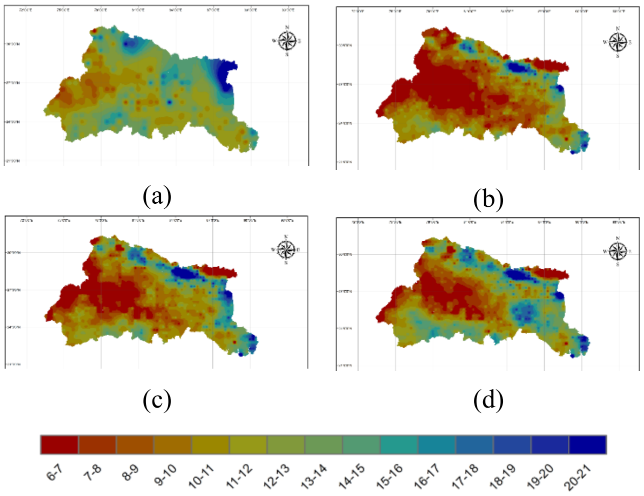

Figure 10 : Spatial plot of Number of days when precipitation > 20 mm (R20) at base (a), 2020's (b), 2050's (c) and 2080's (d) during monsoon (JJAS).

8. Probability Analysis of Extreme Rainfall Events

A probability distribution function (PDF) plot shows the occurrence probability of a variable set. In this section PDF plots of rainfall extremes are established to see the occurrence of low and high precipitation extremes. PDF plot are established for precipitation extremes listed below:

1) One-day maximum precipitation (RX1 day, mm);
2) Count of days when rainfall exceeds 20mm (r20mm, days) and
3) Maximum spell of continuous wet days (CWD, days) for baseline and A1B scenario.

Rainfall extremes are calculated at each grid for Ganges Basin during monsoon season (June, July, August and September) using RCLIMDEX [17] software. Probability distribution function plot for Ganges river basin are established from calculated rainfall extremes at each node. For monsoon season probability distribution functions are plotted in **Figure 11** for three different time periods d, viz. near (2020s, i.e. 2011–2040), farther (2050s, i.e. 2041–2070) and transient (2080s, i.e. 2071–2099).

Probability distribution functions plot are done by math wave software [19] which supports 55 probability distribution functions. It is very important to identify the best probability functions which can precisely depict probability of precipitation extremes. For that purpose a comparative statistical analysis was performed to see the goodness of fit. The goodness of fit tests are checked using Kolmogorov-Smirnov, Anderson-Darling and Chi-Squared tests. It is observed that "generalized gamma" (**Table 2**) is the most suitable probability distribution function for PDF plot.

PDF plot of RX1 and CWD shows positive shift in precipitation extremes in A1B scenario indicates increasing of high precipitation extremes and reduction of low precipitation extremes.

Table 2: Goodness of fit for different probability function

Serial No.	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared	
		Statistic	Rank	Statistic	Rank	Statistic	Rank
1	Gen. Extreme Value	0.032	2	3.15	1	30.83	11
2	Gen. Gamma	0.031	1	3.18	2	26.01	6
3	Log-Gamma	0.050	28	9.44	29	25.06	4
4	Log-Pearson 3	0.040	14	4.68	14	53.36	25
5	Lognormal	0.046	22	6.79	25	22.51	2
6	Lognormal (3P)	0.036	7	3.92	7	36.28	15
7	Normal	0.065	36	12.63	36	122.99	39

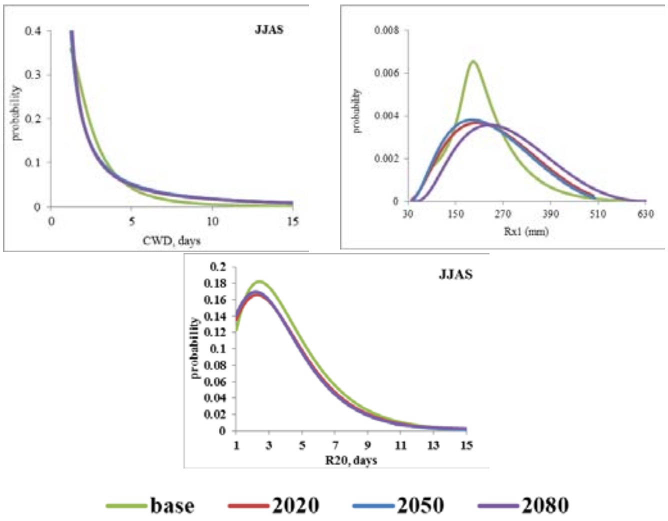

Figure 11: Probability distribution function of daily intensity, (a), CWD days; (b) RX1 mm; (c) R20 day, for baseline (1971–2000), A1B scenario 2020's (2011-2040), 2050's (2041-2070) and 2080's (2071-2099) during monsoon (JJAS)

9. Summary

This study has taken an attempt to evaluate possible changes of rainfall patterns, intensity and frequency in future considering climate change over the Ganges basin. Regional climate model projections are calibrated with the historical data to avoid systemic biases exists between modeling system and observed climate. Future changes are quantified due to natural climate fluctuations as well as anthropogenic forcing such as greenhouse gas increase for the moderate emission scenarios SRES A1B. This study finds the following important facts:

- Seasonal rainfall intensity will decrease in most of the catchments. Hence during monsoon overall rainfall intensity will reduce therefore drier climate is expected.
- Drought prone area will be extended in the future as spatial map of monsoon intensity and precipitation extremes show increasing coverage of low rainfall event.
- Probability plot of RX1 and CWD shows positive shifting of precipitation indices.

- Increasing probability of maximum one day rainfall indicates the possibility of storm event.
- Spatial plot shows that precipitation intensity and precipitation extremes will decrease in Rajasthan, Haryana and this places lies within catchment 13.
- Change in seasonal rainfall intensity in the projected period and a trend of historical rainfall variation reveals the Ganges river basin will have a drier climate.

10. Scope for Future Study

In this study projected rainfall characteristics was analyzed according to AR4 moderate emission scenario. The AR5 scenario has been released recently by IPCC. Hence, rainfall projection with new AR5 scenario would give a more recent and updated idea.

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