Changing pattern of heavy rainstorms in the Indus basin of India under global warming scenarios

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Estimation of extremely high rainfall (point or areal) is one of the major components of design storm derivation. The estimation of Probable Maximum Precipitation (PMP) involves selection of heavy rainstorms and its maximization for the moisture content during the rainstorm period. These heavy rainstorms are nothing but the widespread heavy rainfall exceeding a certain threshold value. The present study examines the characteristics of heavy rainstorms in the Indus basin selected from present climate and future scenarios simulated by the regional climate model. Such information on heavy rainfall forms the basis for the hydrologic design projects and also for the water management of a river basin. Emphasis is given to severe rainstorms of 1-day duration covering an area of at least 40,000 km² with spatial average rainfall of at least 5cm. This analysis also provides the information on the temporal changes in the storm factors such as shape, orientation, and movement, and shows that the model can well simulate the rainstorm pattern in terms of its intensity, orientation, and shape of the rainstorm, but overestimates the frequency of such heavy rainstorms. The future scenario indicates increase in rainfall intensity at the center of the rainstorm with decreasing areal spread. Decrease in the frequency of rainstorms is projected under the global warming conditions.

1. Introduction

Water availability in India is driven by the monsoon systems. Rainfall is the main source of fresh water, which is predominantly controlled by the summer monsoon in central parts of India and by some extra-tropical systems in the northern parts of the country. Due to spatial and temporal variations in rainfall and its highly uneven distribution during the season, some river basins fall in the category of water stress/scarcity, while some river basins suffer from flooding every year. Population growth, increase in water demand, deterioration of water quality, and climate change impacts are some of the issues that increase the importance of water resource management. Flooding has always been

an issue in the northern and northeastern parts of the country.

One of the important problems in hydrology deals with interpreting past records of hydrologic events in terms of future probabilities of occurrence of rare events. Study of such extreme events, which are the root causes of natural disasters is therefore of prime importance. Re-examination of engineering design criteria and allocation policies are needed in the light of climate change impacts. Design of major structures, such as dams, are based on the estimate of very high return period values such as Probable Maximum Precipitation (PMP). World Meteorological Organization (WMO 1986) defines the PMP as 'the physical upper limit for the rainfall for a given area and duration that would

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result from the most critical meteorological situation'. Analysis of heavy rainstorm is one of the major steps in the estimation of PMP. A rainstorm is defined as 'a spatial distribution of the heavy rainfall, yielding an average depth of precipitation that equals or exceeds a certain threshold value over a region in association with some meteorological phenomena', namely, low pressure areas, depression, or cyclonic storms, etc. (Abbi 1972). The most commonly used approach for the estimation of PMP in India, involves rainstorm selection and its maximization for moisture availability using historical records of dew points. This method maximizes the storm efficiency under the hypothetical conditions of maximum moisture availability in the atmosphere. Some of the earlier comprehensive studies in India are by Dhar and Kamte (1969), Rakhecha *et al.* (1992, 1996) and Mandal *et al.* (2004). These studies involve estimation of design criteria, such as PMP, for major or minor hydraulic structures over different parts of the country. Indian Institute of Tropical Meteorology (IITM 2007) carried out design storm estimation and brought out PMP atlases for the Krishna and the Indus river basins in India. The method of rainstorm selection and its maximization has been employed worldwide. Collier and Hardekar (1996) used a storm model for the estimation of PMP. Many recent studies indicate an increasing trend in the frequency and intensity of extreme precipitation events in India (Klein Tank *et al.* 2006; Goswami *et al.* 2006). Since extreme rainfall series at a place is the basic input in the estimation of PMP, temporal changes in extreme rainfall would greatly affect PMP estimation. Easterling and Kunkel (2011) studied the impacts of climate change on the estimation of PMP in USA and indicated by Clausius-Clapeyron relationship that increase in temperature results in increase of saturated water vapour pressure leading to development of intense precipitation-producing systems. Thus global warming could lead to increased PMP values (Tsonis 2002). With this view, it is important to understand the changing rainfall patterns in terms of its extreme behaviour. Though large spatio-temporal variability is seen in rainfall, it is possible to project rainfall patterns using climate model simulations. Regional climate models (RCM) that capture well the local features affecting the climatology of an area are the basic tools used to project future climate scenarios. Selection of heavy rainstorms is the major step in the estimation of PMP. Analysis of severe rainstorms of different magnitudes and durations is a basic tool for safe and economical planning and design of small dams, bridges, culverts, irrigation, and drainage works, etc.

Another important aspect of the rainstorm analysis is the areal rainfall distribution at a place which is essential for efficient design of hydraulic structures such as dams, urban storm sewers, highway culverts, and water-supply facilities. Literature is available on the distribution of point rainfall, but very little information is available on the areal distribution of rainfall. It is a general practice to use areal reduction factor to convert point rainfall depths to basin area. Hershfield (1961) and Huff and Vogel (1976) were among the first few researchers who presented area rain depth curves for estimating areal mean rainfall from point rainfall using station network in USA. Rakhecha and Rakhecha and Clark (2002) evaluated distribution of areal rainfall for the first time for India.

Accordingly the main objective of the present study is to assess the impact of global warming on spatial distribution of rainfall during rainstorm, shape, orientation, and movement of the rainstorms. This is achieved by analyzing heavy rainstorms in the Indus basin selected from the station daily rainfall records (1901–2005) and future rainfall projections using high resolution regional climate model. Baseline rainfall simulations have been used to examine the model efficiency in generating the baseline climate.

2. Study area

The Indus River rises in Tibet near Mansarovar Lake at an elevation of 5180 m, flows through mountain ranges in northern Kashmir and Gilgit, enters Pakistan and emerges out of the hills near Attock (Rao 1975). After flowing for a distance of about 2880 km, it meets the Arabian Sea. The entire Indus basin extends over an area of about 11,54,500 km² out of which the drainage area lying in India is about 321,290 km² (nearly 9.8% of the total geographical area of India). The basin lies in the states of Jammu & Kashmir (~193,762 km²), Himachal Pradesh (51,356 km²), Punjab (50,304 km²), Rajasthan (15,814 km²), Haryana (9939 km²), and Union Territory of Chandigarh (114 km²). Major tributaries of the Indus are the Kabul, the Swat, and the Kurd from the west and the Jhelum, the Chenab, the Ravi, the Beas, and the Sutlej from the east. Tributaries from the west are not considered in the study as their basin areas lie outside India. Northern parts of the basin are covered by glaciers. Generally elevation of approximately 4000 m is considered the permanent snowline over the Indus basin (IITM 2007). Areal rain depth is calculated for only rainfed area of the basin. The entire Indus basin in India has been divided into seven sub-basins 201–207

(Khosla 1949). Details of these sub-basins along with snow covered area in these sub-basins are given in table 1.

3. Data used and methodology

Different datasets such as observations and model simulations have been used in the study;

1. Daily rainfall data for the period 1901–2005 of nearly 200 stations (with variable data period but at least for 50 years) is used to select and study the rainstorm characteristics in the present climate and also used for model validation. Figure 1 indicates the locations of the stations, topographical features and different sub-basins of the Indus basin.
2. High resolution Regional Climate Model PRECIS (Providing REgional Climatolgy for Impact Studies) developed at Hadley centre (UK) is used to obtain the daily rainfall simulations for baseline and future climate data. PRECIS simulations (A2 scenario) with the resolution of $0.44^\circ \times 0.44^\circ$, lat./long. for the period 2071–2100 (Rupa Kumar *et al.* 2006) are used to project the rainstorm characteristics at the end of 21st century under the global warming conditions. Model generated baseline dataset (1961–1990) is used for the validation of model simulations. Details of PRECIS model are given here.

3.1 PRECIS regional climate model

PRECIS is a portable Regional Climate Model (RCM) that can be run on a personal computer and can be applied to any part of the globe to generate

detailed climate change scenarios. The present study uses high resolution PRECIS simulations under CMIP3 experiments that are available in public domain. PRECIS generates fine-scale information on regional climate using coarse resolution information from a Global Climate Model (GCM) and also regional information on certain parameters such as land use/land cover, etc. PRECIS is run for gradual increase in greenhouse gas

Figure 1. Location of stations and topographical features of Indus sub-basins.

Table 1. Sub-basins of Indus river along with total area and snowfed area (in km²).

Sub-basin	Description	Area (km ²)	Approx. snowfed area (km ²)	Seasonal rainfall (cm)			
				Winter	Pre-monsoon	Monsoon	Annual
201	River Sutlej upto Bhakra Dam Site	23044	14843	30.3	22.3	62.2	120
202	River Sutlej between Bhakra Dam site and Beas excluding Beas	67398	Nil	8.4	7.7	44.5	63.1
203	River Beas	20894	3577	29.2	23.5	101.7	160.2
204	River Ravi	14834	1038	29.3	18.6	94.5	149.2
205	River Chenab	29493	15263	41.8	23.9	65.2	136.2
206	River Jhelum	29901	4571	39.2	27.4	18.4	97.6
207	River Indus up to Pakistan boundary	135726	135726	9	5.6	2.7	19.3
Entire		321290	175018	22.4	16.3	50.1	93

concentrations per year. Such runs representing the global warming scenario are obtained for recent climate period (baseline simulations for 1961–1990) and also for the future projections (2071–2100) considering the future concentrations calculated from one or more emission scenarios developed by the Inter Governmental Panel for Climate Change (IPCC). The baseline period 1961–1990 represents that there are no increases in emissions as per IPCC reports (i.e., to represent pre-industrial climate). 1961–1990 is therefore used here to represent the baseline state of the climate to examine the impact of climate change. Future scenarios are commonly taken at the end of the century (i.e., 2071–2100) when the climate change signal will be clearly seen against the noise of climate variability (Jones *et al.* 2004).

Before proceeding further to select rainstorms from the observation dataset, the dataset undergoes quality checks to ensure the accuracy and consistency of the results. Station data have been examined to detect the outliers in the daily rainfall values. As daily rainfall data follows right or positive skewed distribution, 3 sigma criteria for detecting outliers is not suitable and therefore 5 sigma criteria is used. Values going beyond this threshold are detected and then correctness of these values are examined either from available literature or from the daily weather report of IMD. If such high values are found to be correct, they are included in the analysis, otherwise treated as missing. No treatment is applied to the missing data. Filling up of missing daily rainfall data in extreme rainfall analysis is inappropriate as most of the rainfall events are abrupt in time and space. So filling these values may lead to dubious results in extreme rainfall analysis.

Methodology involves the selection of the heavy rainstorms of 1 day duration from the daily rainfall data, namely, observational, baseline, and future projections from PRECIS. The following criteria is used for the selection of the rainstorm:

A rainstorm with the spatial coverage of 40,000 km² area or more and central rainfall value exceeding 20 cm/day, is selected as severe rainstorm occurring in the Indus basin. To define the boundary of the rainstorm, peripheral isoline is taken as 5 cm. To make the valid comparison between rainstorms during the period 1961–1990 based on observed station daily rainfall data and baseline datasets generated by RCM, station data during the rainstorm period are transformed to gridded dataset with the same grid size as that of PRECIS format. Inverse squared distance method is used for transformation and then rainstorm patterns are displayed using GrADS 1.9.0-rc1. As the gridded data from PRECIS is used with the grid size $0.44^{\circ} \times 0.44^{\circ}$ (nearly 2500 km² area), point rainfall or rainfall for the area less than 2000 km² is

obtained by extrapolating area-rain depth curve for each rainstorm. These curves are obtained by plotting the area enclosed by each isoline against the corresponding average rainfall depths. The smooth depth-area curves and other results are discussed in section 5.

4. Meteorological causes of heavy rainfall over the basin

As the analysis is concerned with extreme rainfall in Indus basin, some of the meteorological situations when the Indus river basin records heavy rainfall are documented here. The basin is characterized by different climatic conditions from tropical to alpine. The upper portion of the basin (north-western part) receives good rainfall during the winter season due to the passage of Western Disturbances across the Himalayas. These disturbances are eastward moving low-pressure areas or upper air troughs in the subtropical westerlies. During winter, the frequency of these disturbances is of the order of 4 to 6 per month, reducing as the season advances (Dhar *et al.* 1987). The sub-basin 206 located in Kashmir valley is saucer shaped with steep mountain slopes all round. Annual rainfall of this area is 100 cm, 40% of which occurs in the winter season. Heavy rainfall of 1–2 days duration can cause severe floods. The precipitation associated with these disturbances decreases sharply as they move from west to east along the Himalayas. Sub-basin 203 records the highest rainfall in the basin. The summer or pre-monsoon season lasts for about 3 months from April to June. Western Disturbances do occur in this season but their average frequency is about 2–3 per month (Dhar *et al.* 1987). During the southwest monsoon months of July to September, sub-basins 201 to 205 come under the influence of moist monsoon current from the Bay of Bengal and the Arabian Sea (figure 2). Average rainfall of this area ranges from 63–160 cm/year (Deshpande *et al.* 2008). The sub-basin 207 falling in the Ladakh region is located in the worst arid region of India due to lack of rainfall, which is around 19 cm/year. All months receive rainfall but with very negligible quantity. Therefore, no specific season may be marked in this region. During the period July to September moderate to heavy rainfall occurs over the Indus basin in association with the following weather situations as shown in figure 2:

- (a) Re-curling monsoon depressions or low pressure areas from the Bay of Bengal or the Arabian Sea dissipating over the basin,
- (b) movement of westerly waves (or Western Disturbances) over the northern portion of the

basin synchronizing with the passage of monsoon disturbances in the lower latitudes

- (c) movement of upper air cyclonic circulations over the basin and or
- (d) shifting of monsoon trough near the foothills of the Himalayan region during break monsoon situations.

Some past incidences of heavy rainfall that caused catastrophic flooding in the Indus basin are summarized here:

Figure 2. Meteorological situations favourable for causing heavy rainfall over the Indus basin.

Indus basin experienced catastrophic rainfall in the first week of September 2014 witnessing its worst flood in last 50 years. At many places, Jhelum River crossed its danger mark. Several weather stations in the basin broke their previous records of 24-hr, 48-hr, and monthly rainfall of September month. 24 September 1988 and 5 September 1995 were two incidences when most of the parts of Kashmir received heavy rains resulting in flood conditions in the river basin. Pakistan flood of July 2010 was one such devastating flood resulting from heavy monsoon rains in the Indus basin. In all these events, topography played an important role in transferring rainwater to the stream flow in a very short period of time causing flash floods. Long duration of heavy rainfall increased the flood intensity.

5. Results and discussions

Study on future projected heavy rainstorms involves analysis of heavy widespread rainfall events in the basin. Before proceeding further for the analysis of heavy rainstorms, an attempt has been made here, to assess the future projected changes in the 1-day extreme rainfall in the basin.

5.1 Future projections of 1-day extreme rainfall

Figure 3 depicts the spatial patterns of 1-day extreme rainfall as seen in daily observed rainfall dataset (left panel) and percentage change in the extreme rainfall amount as projected by the model under global warming scenario (right panel). The figure shows that heavy rainfall of 35 cm

Figure 3. Spatial pattern of 1-day extreme rainfall and projected changes (%).

and more has been recorded around the location (31°N , 76°E) during one day. Extreme rainfall values decrease towards north-east and southwest direction in the basin. Percentage change in the extreme rainfall during the period of 30 years of simulations indicate that except for a small area in the western and eastern parts of the basin, 1-day extreme rainfall at grid level (area of 2500 km^2) is projected to increase in the basin at the end of 21st century, highest being in the central part of the basin. To examine the extreme rainfall changes on a larger spatial scale, depth-area analysis has been carried out for observational data set and model simulations of present and future climate.

5.2 Depth-area analysis

Using the criteria for the selection of heavy rainstorms, as mentioned above, severe rainstorms were selected from the observational as well as model simulated datasets representing baseline and future scenarios. In all 5 rainstorms from observational data, 12 from baseline data and 4 from future simulations have been selected that satisfy the criteria used. Table 2 gives the list of rain-

storms and corresponding year/period of occurrence. Note that future scenarios are the projections and not the predictions therefore, the frequency of these rainstorms, in the period of 30 years just represents the number of occurrences in that period. It may not occur in the same year as indicated. Rain depth-area analysis has been carried out for all the selected rainstorms of 1-day duration. Areas enclosed between two consecutive isolines starting from the innermost isoline up to the peripheral isoline of 5 cm have been computed. Cumulative areas are then plotted against the average areal rain depths to yield the raindepth-area curves. Average rain depths (cm/day) corresponding to some standard areas (up to $70,000\text{ km}^2$) are listed in table 2, though some rainstorms are spread over the area of more than one lakh sq. km. Figure 4(a and b) indicates the spatial patterns of the rainstorms and corresponding rain depth-area curves along with smooth envelope curve of the observational rainstorms. Figure 4(a) indicates that the centres of these rainstorms are located near 32°N , 76°E . The combined effect of re-curvature of monsoon disturbance and occurrence of western disturbance in the mid-latitudes moving from west to east and also orographic effect of the region play an important role in

Table 2. Severe rainstorms recorded in the Indus basin during the period 1971–2010 and areal raindepths (cm/day) (range is given in bracket for baseline and future scenarios).

Rainstorms	Area (km^2)							
Observed	100	1000	2000	5000	10,000	20,000	50,000	70,000
1. September 24, 1988	36.2	35.5	34	30	20	16.5	12	9.9
2. September 4, 1995	22	21.5	20.8	20	18	15	11.8	9.8
3. July 16, 1975	24	23	22	16	13.8	11.2	—	—
4. July 10, 1993	26.9	24	22	16	10	9	6.4	—
5. August 23, 1996	21.7	21.4	21	20	15	10	8.4	7.2
Baseline rainstorms (12 rainstorms have been selected using the criteria)								
1. September 1962	50.1	48.3	47	45	21	18	12.5	8.5
2. September 1965	36.1	35.9	34	32	26	21.4	12.6	9.3
3. October 1968	35.1	33	31	27.3	18.6	16.5	10.1	5.8
4. October 1970	35.3	34.2	33.3	27	25.8	22.1	11.7	7.8
5. September 1972	42.4	41	36.7	31.8	21.5	16	10.5	6.6
6. October 1973	33.3	31.8	27.5	25.3	21.3	17	8.3	—
7. September 1979	33.1	30.4	28.6	26	22.2	17.4	9.5	5.5
8. September 1979	37.4	36	35.3	30	23.5	17.2	10	6.5
9. July 1981	32.6	31.1	29.9	27.4	20.7	18	9.5	5.1
10. September 1982	34.5	32.6	31.8	30.2	26.8	19.1	8.5	5.2
11. September 1984	28.6	27.2	26	24	22.4	20	14.7	10.6
12. September 1986	30.4	28.3	27	25	19.4	13.5	8.8	—
Future simulations (4 rainstorms have been selected)								
1. July 2085	52	42.5	40.7	32	27	19.2	10.1	—
2. July 2085	34.1	33	31.6	29.5	26	15	7.5	—
3. August 2085	38.8	37.2	35.5	33	27	20	5	—
4. July 2086	46.2	42	38	35	22.5	15	—	—

Figure 4. (a) Spatial patterns of observed rainstorms and (b) depth-area curves with envelopment for observational rainstorms.

causing the heavy rainfall amount at this location. These rainstorms are of elongated nature with their orientation either in north-south or in southwest to northeast direction. Figure 4(b) indicates that

rainstorm of 1988 was the most severe covering the area of 130,000 km². Raindepth-area curve of this rainstorm envelopes raindepth-area values of the remaining rainstorms.

Figure 4. (Continued.)

From table 2, it is observed that the rainstorm of 24 September 1988 was the most intense rainstorm during the observational period with center at Nawanshahr station in Jullundar district of Punjab (location: 31°N , 76°E) received 51 cm of rainfall on 24 September 1988 and covering the area of more than $130,000 \text{ km}^2$ (IITM 2007; Nandargi and Dhar 2012). Area affected by the rainstorm of July 1975 was around $41,000 \text{ km}^2$. Two rainstorms out of the selected 5 (1993 and 1996) were on the border of the basin and their centres lie outside the basin. All these observed rainstorms were recorded in the monsoon months of July–September. They were associated with cyclonic storms originating in Bay of Bengal together with the interaction of western disturbance moving across the basin.

Spatial patterns of rainstorms selected from baseline simulations and raindepth–area curves (along with smooth envelope curve) are shown in figure 5(a and b). It is seen that all the rainstorms are located in the central part of the basin. Except for a few rainstorms such as October 1968, October 1970, and July 1981, orientations of other rainstorms as projected by the Regional Climate Model are either north–south or southwest to northeast similar to rainstorms from observational data. Shape of these rainstorms are not that elongated as compared to the observed rainstorms. Figure 5(b) indicates that three rainstorms simulated by the model, namely, September 1962, September 1965, and September 1984, contribute to the envelope curve. Area coverage of these rainstorms is more, as compared to the observed rainstorms ranging from $67,000$ to $141,750 \text{ km}^2$. Baseline simulations indicate occurrence of such heavy rainstorms at the end of monsoon season or even in the month of October as seen from table 2.

Future projected rainstorms are shown in figure 6(a and b). Only four rainstorms satisfy the selection criteria of severe rainstorms. Figure 6(a) indicates that except rainstorm of July 2086, others are oriented in southeast to northwest direction. Centres of all the four rainstorms are located along 32°N latitude. Figure 6(b) shows raindepth–area curves for these rainstorms along with the smooth enveloping curve. Area coverage of these rainstorms is less than $70,000 \text{ km}^2$, with centre rainfall value of the order of 50 cm/day . Occurrences of future projected rainstorms simulated by the model are in the monsoon months.

It is clear from the baseline simulations that the model overestimates the frequency of heavy rainstorms, while, future projections indicate that central value may be of higher order (more than 50 cm) compared to the baseline simulations, but its areal spread would be less. Such rainstorms may be less frequent but more intense in future as projected by the PRECIS model. Model baseline simulations indicate delay in the occurrence of the rainstorm over the basin at the end of season. It is observed that most of the selected rainstorms are located around the location 32°N , 76°E , i.e., area located on the hilly slopes of Kangra valley in Himachal Pradesh. So orography plays an important role in the occurrence of heavy rainfall over this area. Dharamsala, located in this part, is the station receiving heavy rainfall every year (annual rainfall of 310 cm).

5.3 Relationship between central rainfall and its areal spread of a rainstorm

Hydrologists and design engineers need a relationship to convert point rainfall to average rainfall

Figure 5. (a) Spatial patterns of model baseline rainstorms and (b) depth-area curves with envelopment for model baseline rainstorms.

Figure 5. (Continued.)

over a specified area. Raindepth-area curves can be used to determine the area reduction factor. General pattern of a rainstorm is that maximum intensity of rainfall occurs at the centre and then it gradually decreases towards the periphery. Kulkarni *et al.* (2010) fitted a non-linear expression to relate point rainfall to areal rainfall of a rainstorm. The form of the equation used is:

$$p(a) = p(0)e^{-ka^n}$$

where $p(a)$ is maximum areal rain depth corresponding to the area a . $p(0)$ is the central rainfall value. k and n are the constants to be determined from depth-area values of selected rainstorms. The unknown constants are estimated by least square method. Table 3 gives the estimated constants (k and n) and Root Mean Square Error (RMSE) in fitting the above equation to the average raindepth-area curves of selected rainstorms from the three datasets. Figure 7 shows average rain depths and fitted exponential rain depths for observed, baseline, and future projected rainstorms. It is seen from table 3 and figure 7 that the non-linear relationship, as indicated above, fits well to the average raindepth-area values. Table 3 indicates that RMSE calculated from observational rainstorms is smaller than that of baseline and future projections. However, the difference is very small. Therefore such relationships can be further used for estimating areal rain depths corresponding to size areas different from the point rainfall values.

5.4 Rainstorm shape, orientation and movement of heavy rainstorms

Runoff characteristics of a river basin are influenced by the shape, orientation, and movement of

the storms during heavy rain spells. To assess the flood potential of extreme rainfall events at a place such information is necessary.

Shape parameter of a rainstorm is determined by the ratio of its major to minor axis, while, orientation is determined by the angle made by the major axis to the north direction. An attempt has been made here to study the characteristics of heavy rainstorm under climate change scenarios. It has been observed that heavy rainstorms usually exhibit an elliptical shape in the river basin. This shape becomes more elongated with increasing area. In the present analysis, isoline of 10 cm has been used for deciding the shape and orientation of the rainstorm as the peripheral isoline of 5 cm has no definite shape for some of the selected rainstorms. Table 4 gives the shape parameter and orientation of all the severe rainstorms considered here from observational datasets as well as average shape parameter from the baseline and future projected rainstorms. It is seen from the table that shape parameter for observed data ranges from 1.4 (16 July 1975) to 3.4 (4 September 1995) averaging to 2.1, while shape parameter for baseline rainstorms ranges from 1.2 (September 1972) to 3.1 (October 1970 and July 1981) averaging to 1.9, which is less than that of observed rainstorms, indicating that shape of the rainstorm generated by the model simulations is less elongated. Shape parameter for the future projections ranges from 1.4 (July 2086) to 2.7 (July 2085) averaging to 2.1 similar to that of observed. No substantial change in the shape parameter is observed in future projections.

The orientation of the storm axis also provides an indication of the movement of the rainfall bearing synoptic system. If the major part of this axis lies in the basin it causes heavy widespread rainfall in the basin causing sudden rise in the total run-off. Orientations of all the observed storms and

Figure 6. (a) Spatial patterns of future projected rainstorms and (b) depth-area curves with envelopment for model future projected rainstorms.

average orientation (indicating the frequent occurrence) based on baseline and future projected rainstorms are given in table 4. Table 4 shows that all the observed rainstorms, except August 1996, are oriented almost in north-south direction in the basin, while in baseline simulations, orientation

ranges from -80° (July 1981) to 40° (September 1972) with average value of -5° , i.e., approximately in north-south direction similar to observed rainstorms. But future model projections indicate orientation may be in southeast to northwest direction under global warming scenario (ranging from

–45° of July 2085 rainstorm to –65° of August 2085 rainstorm with average of –60°).

Each rainstorm is associated with a certain synoptic system as discussed in the earlier section. Each system has its own path of movement. It may be a cyclonic storm originating in Bay of Bengal moving in northwest direction and re-curving to northeast direction giving heavy rainfall to the southern portion of the basin. Western disturbances originating in the west of the basin and moving towards east also cause heavy rainfall over the entire basin. Synoptic observations during the storm period indicate that movement of all the storms were from either south or southwest to north or northeast direction. Movement of future projected rainstorms from southeast to northwest direction indicate northward shift in the path of monsoon disturbances.

Table 3. Estimates of 'k' and 'n' in fitted equation to average depth-area values and RMSE in the estimation.

	k	n	RMSE
Observed	0.0329	0.3215	3.62
Baseline	0.0334	0.3223	4.68
Future	0.0118	0.4246	4.48

6. Summary and conclusions

The present study analyzes the severe rainstorms in the Indus basin of India, selected from observed, baseline, and future projections of daily rainfall. Spatial distribution of 1-day extreme rainfall, widespread rainstorms as well as its shape, orientation, and movement have been examined in the study. Main conclusions of the present analysis are given below:

1. Rainstorm of 24 September 1988 was the most intense rainstorm enveloping all the depth-area values of historical rainstorms during the observational period. Baseline simulations indicate that the model overestimates widespread rainfall events. Future projections indicate less frequent rainstorms with increase in the central value and decrease in its areal spread.
2. Extreme rainfall is projected to increase in almost all parts of the basin, highest being in the central part of the basin.
3. Average raindepth area relationship is well represented by exponential fit and can be used further to determine areal rain depths using the central rainfall value.
4. Baseline simulations indicate that shape and orientation of the rainstorm is generated well by the model. No substantial change in the shape

Figure 7. Average raindepths and fitted exponential curve for (a) observed, (b) baseline and (c) future projected rainstorms.

Table 4. Shape parameter (ratio of major to minor axis) and orientation (angle made by major axis w.r.t. north direction).

Rainstorm	Shape parameter	Orientation (angle in degree with north direction)
24 September, 1988	2.1	0
4 September, 1995	3.4	5
16 July, 1975	1.4	–5
10 July, 1993	1.3	–5
23 August, 1996	2.5	35
Average baseline rainstorm	1.9	–5 (north–south direction)
Average future projected storm	2.1	–60 (northwest to southeast direction)

of the rainstorm is indicated by future projections. Change in the orientation and movement of a rainstorm is indicated by the model under global warming scenario.

Projections should be considered carefully as large bias is seen in the baseline model simulations compared to observed rainstorms. Uncertainty associated with the results can be further reduced by considering multi-model ensembles of future projections from CORDEX. This work was initiated before the availability of CORDEX simulations. Now model outputs for 4 RCMs in CORDEX have been made available to users, hence in future similar analyses will be carried out with these multi-model simulations to examine the efficiency of these models in generating widespread heavy rainfall over different river basins of India.

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