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Characteristic features of hourly rainfall in India

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ABSTRACT: Hourly rainfall data recorded at 72 Self Recording Raingauge Stations (SRRG) for the period 1969–2006 are utilized to study the characteristic features of hourly rainfall and diurnal variations of rainfall in India. Temporal changes in the short duration (less than 12 h) rainfall extremes are examined. Time distribution of a heavy rain spell of 24 h duration, which is an important component in water resources management and flood control studies, is analysed. Different aspects of hourly rainfall such as, average number of rain hours in a year, empirical probability distribution functions have also been examined. Analysis indicates, many stations in India have recorded more than 10 cm of rainfall in an hour's duration. Such stations are located along the west coast, foothills of Himalayas and along the tracks of monsoon disturbances. Extreme rainfall events of various duration (3–12 h) show increasing trends, significant at 5% level, at many stations located in central India and peninsular India except for southern part of west coast. Time distribution of hourly rainfall shows that, on average, 25% of the daily rainfall can be received in just 3 h, while 80% can occur in 12 h during the heavy rain spells of 24-h duration. Copyright © 2011 Royal Meteorological Society

KEY WORDS heavy rain spells; extreme rainfall; rain hour; diurnal cycle of rainfall; time distribution of rainfall

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1. Introduction

The climate of India is dominated by monsoon systems. During the northern hemispheric summer, southwesterly winds bring moisture from the Indian Ocean and give heavy rains across India during June to September. The climate of India is broadly divided into four seasons, primarily demarcated by the seasonality in rainfall: (1) Winter (January and February); (2) Pre-monsoon (March to May); (3) Southwest monsoon (June to September); (4) Post-monsoon (October to December). Seasonal (4 seasons) and annual rainfall distribution across India is shown in Figure 1. On average, India receives 105 cm of rainfall in a year out of which summer monsoon (or southwest monsoon) contributes nearly 75–80% to the annual rainfall at many parts of the country. A salient feature of monsoon rainfall is the movement of depressions/storms originating over Bay of Bengal or Arabian Sea. However, the northern tip of India receives a substantial amount of rainfall during winter season on the account of western disturbances. Pre-monsoon rainfall activity or thunderstorm activity prevails over some parts of India such as northeast India. Southeast peninsula experiences its wettest season during October to December or post-monsoon season.

Generally, information on rainfall climatology is available for time scales such as monthly, seasonal or annual rainfall, which is derived from the daily rainfall amounts recorded at individual stations. It is also important to know the climatic features of rainfall on shorter time scales such as daily, hourly and even minutewise, for the management of drainage systems, agricultural operations and soil erosion studies, etc. The mean diurnal cycle of rainfall in terms of short-duration precipitation can provide interesting insights on the local rainfall characteristics that may have important implications for efficient water resource management. Many places in India have recorded 40–100% or more of their mean annual rainfall in one day (Dhar *et al.*, 1982). It has been observed that at some places, on an extreme rainfall day, nearly 60% rainfall is received in just a few hours causing flood situations in the downstream area due to insufficient storage capacity of the reservoirs for accommodating the excess rainwater. Such situations are very common in northeast India and in the Indo-Gangetic plains. Santacruz (Mumbai) a station on West Coast of India, recorded 94.4 cm of rainfall on 26 July 2005. Out of which 38.1 cm (40%) of rainfall was received in just 3 h due to cloud burst phenomenon, while 56.3 cm (60%) was received during 15 h and it was associated with continuous regeneration of thunderstorm activity (Vaidya and Kulkarni, 2007).

Diurnal variations in the rainfall patterns have been a focus of the scientific literature for many years. Bleeker and Andre (1951) examined the nocturnal rainfall patterns over the central US and attributed it to the circulation systems developed by the heating/cooling processes during day/night time. Kousky (1980) examined the effect of local wind systems and orography in producing rainfall over northeast Brazil, indicating a significant link between the local wind circulation systems in the form of mountain and valley breezes. Several previous studies have identified the modulating role of orography as

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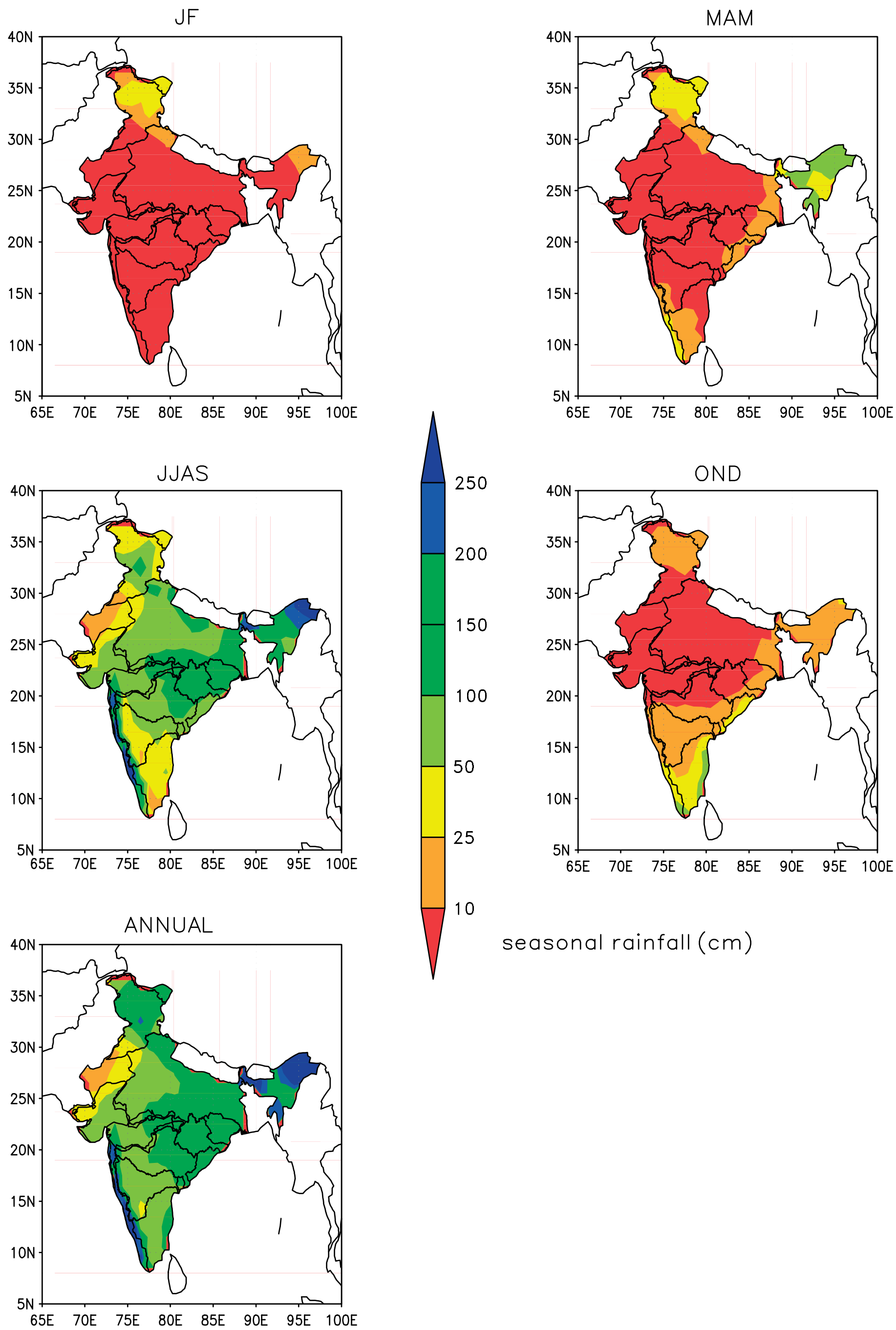

Figure 1. Seasonal and annual rainfall (cm) over India. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

a major factor in the convectional process affecting the diurnal patterns of the rainfall in the tropics (Yang and Slingo, 2001). Many studies available on hourly rainfall data over the Indian region, describes diurnal variation during summer monsoon season or a particular season in India (Ananthakrishnan and Rajan, 1987; Haldar *et al*., 1991; Sen Roy and Balling 2007).

Another important aspect of hourly rainfall is the distribution of rainfall during a heavy rain spell of 24 h duration. Water balance on land surface is highly sensitive to the time distribution of rainfall. It is essential to provide information on the rainfall distribution on a heavy rain day along with the estimation of extreme rainfall event, such as Probable Maximum Precipitation (PMP) at a place, for designing the spillway capacity of the reservoir/dam, etc. of a river basin. PMP is a metric, that is required in designing the major hydraulic structures and its estimation is generally based on daily rainfall records over a long period, say 70–100 years. The distribution of rainfall or breakup of extreme rainfall amounts on the daily time scale into shorter time intervals requires analysis of hourly rainfall records (called as time distribution). Many studies on the time distribution analysis, in the Indian context, are connected with certain hydraulic projects or for certain river basins (Dhar and Ramachandran 1970; Dhar *et al*., 1982; Harihara Ayyar and Tripathi 1974; Rakhecha *et al.*, 1996; Deshpande *et al.*, 2003).

Here we examine some characteristic features of short-duration rainfall at some Indian stations and also the temporal changes in their characteristics during the period 1970–2003. Along with the two aspects discussed above, namely, diurnal variation of rainfall and time distribution of rainfall during heavy spells, other important aspects of hourly rainfall, such as number of rain hours during a year, frequency distribution of hourly rainfall, contribution of the daytime rainfall to monsoon rainfall and spatio-temporal changes in the extreme rainfall of durations less than 12 h, etc. have also been examined in this study. Accordingly, the main objectives of this study are to examine:

1. Spatial and temporal variations in the number of rain hours contributing to seasonal rainfall over India.
2. Temporal changes in the frequency distribution of hourly rainfall amounts.
3. Temporal changes in the diurnal cycle of rainfall.
4. Contribution of daytime rainfall to monsoon rainfall and its variability.
5. Highest ever recorded rainfall for the duration of 1, 3, 6, 12 h over India, and temporal changes in extreme rainfall of short duration (less than 12 h).
6. Average time distribution of rainfall during heavy rain spells of 24-h duration.

2. Data used and methodology

Daily high-resolution gridded rainfall dataset ($1^\circ \times 1^\circ$ lat/lon), prepared by National Data Centre (NDC) of India Meteorological Department (IMD), Pune, India, for the period 1951–2007, is used for generating seasonal and annual rainfall patterns for India. Also 145 stations' hourly rainfall data are obtained from NDC, IMD, Pune. Data quality has been checked by detecting the outliers in the datasets and examining their correctness. Annual time series of 1-h extreme rainfall are constructed for all the stations. Extreme rainfall series does not follow Gaussian distribution, rather they are positively skewed, therefore, for outlier detection a threshold of 5σ (σ is the standard deviation of corresponding extreme rainfall series), is considered. Values lying outside the 5σ–interval of mean annual extreme rainfall series are treated as outliers and their correctness have been checked by comparing them with the same day's rainfall value for the respective station from IMD's Indian Daily Weather Report (IDWR) and from other published literature. Doubtful high rainfall values have been omitted from the analysis. After removing the outliers, analysis considered only those stations possessing data period of at least 25 years of continuous records with 75% data availability for each year. Thus, 72 stations with data period 1969–2006 (with variable data length) have been selected for the analysis. Figure 2 shows locations of these 72 stations and the topography (meters) over Indian landmass. Spatial distribution of these stations indicates a good network over the country excepting some areas in extreme north and extreme eastern India. Table I gives the data availability of these stations. It is seen that data availability varies between 26–38 years for all the stations. Though the analysis was carried out for 72 stations, results on diurnal cycles and empirical PDFs have been shown for some representative stations only.

A nonparametric, Mann-Kendall rank test (Hirsch *et al.*, 1993) is used to detect the monotonic trends in different time series of hourly rainfall over a consistent data period of 1970–2003. This test is more suitable than the parametric '*t*' test, in situations of non-normal data with missing data values, which frequently occur in hydrometeorological studies (Yue and Pilon, 2004).

To examine the temporal changes in the rainfall patterns, datasets have been divided into 2 time periods, 1970–1986 is used as the reference period, and 1987–2003 is used as the recent period. Frequency distribution of hourly rainfall amounts has been calculated separately for both the time periods for stations having data period for 1970–2003.

3. Number of rain hours contributing to seasonal and annual rainfall

India receives a major proportion of its annual rainfall during the summer monsoon season (June to September). It is characterized by large spatial and temporal variations within this season. Even during active phase of monsoon, only few hours contribute more than 90% to its daily total. A rain hour is defined here, as an hour with any measurable rainfall amount. It is shown by Ananthakrishnan and Rajan (1987) that at a station, Cochin, located on the southern part of the west coast (Location: 9.9 °N, 76.3 °E), the exact duration for monsoon rainfall of average 194 cm is just 24 days (i.e. 24 × 24 h of rainfall). Similarly, at Minicoy, an island station located in the Arabian Sea, (location: 8.3 °N, 73.04 °E), 92 cm of average summer monsoon rainfall occurs in the duration equivalent to 54 days. This demonstrates the nature of the intensity of monsoon rainfall in India, which varies widely over different parts of the country. The following section, discusses the number of rain hours during the monsoon season as well as during a year, and the temporal changes during the monsoon season.

3.1. Number of rain hours in India

Figure 3 depicts the climatology of rain hours for summer monsoon season (June–September, left panel) and annual (right panel). Northwest India shows minimum number of rainfall hours around 100 h/yr, while maximum rain hours are seen along the west coast, which are of the order of 800–1000 h/yr or even more. For the rest of the country, the number of rain hours range between 200 and 600 h/yr. During non-monsoon period (excepting June–September), a substantial amount of rainfall occurs over extreme northern India due to western disturbances;

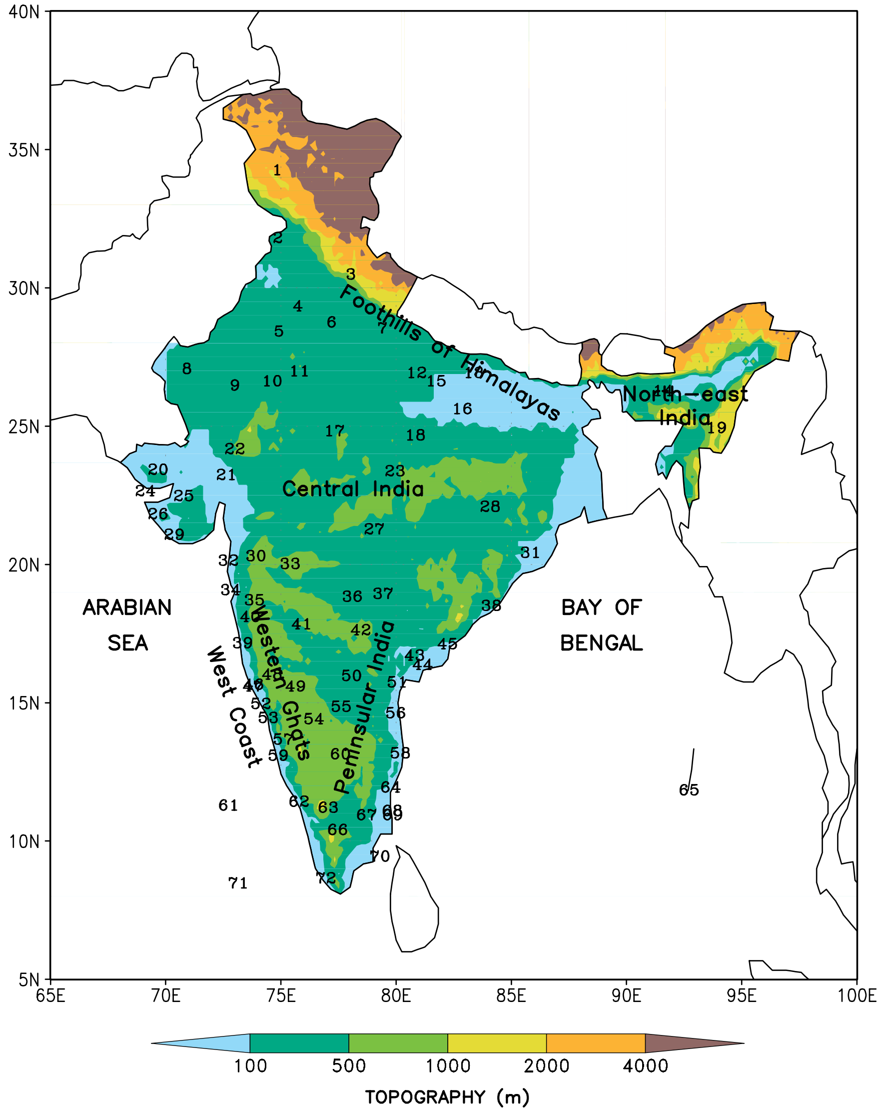

Figure 2. Locations of 72 SRRG stations (marked with serial number as appearing in Table I) and topography (meters). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

in peninsular India due to northeast monsoon activity; and along the Orissa coast due to thunder shower activities in pre-monsoon season (March–May) resulting in large differences over these regions between seasonal and annual patterns of rain hours as seen in Figure 3. The West coast and central parts of India hardly receive any rain during non-monsoon months, hence, over these regions no substantial differences are seen in the spatial patterns of rain hours during the annual and summer monsoon season.

3.2. Trends in number of rain hours

Long-term trends in the time series of number of rain hours, at a place, are examined by the Mann-Kendall test. Figure 4 shows trends in the number of rain hours and stations showing significant change during monsoon season. Some stations in the peninsular India and along east coast show increasing trends (significant at 10% level), while significant decrease (at 5% level) in the number of rain hours is observed at some stations in the central parts of India. This may be due to decreasing trends in the July rainfall over this region (Guhathakurta and Rajeevan, 2006).

4. Frequency distribution of hourly rainfall amounts

Frequency distributions of hourly rainfall at all the 72 stations, have been examined to characterize the nature of rainfall at a place as well as to study the temporal variations in the rainfall distribution in India. As mentioned in the data and methodology section, frequency distributions have been worked out for all 72 stations, for the reference and recent periods separately. It has been observed from the analysis that for most of the stations, excepting from northern and northeast India, both the frequency curves, for the reference and recent periods overlap each other upto certain rainfall value and for higher values, curve for recent period lies above to that of reference period. This indicates no substantial

Table I. Extreme rainfall (cm) for different durations (in hours) for 72 stations.

Sr. no.	Station	Data period	Extreme rainfall (cm)			
			1 hr	3 hr	6 hr	12 hr
1	SRINAGAR	1970–2005	4.0	6.5	9.1	11.1
2	AMRITSAR	1969–2004	9.9	14.1	16.1	16.2
3	DEHRADUN	1969–2005	10.1	24.5	27.9	28.9
4	HISSAR	1970–2005	9.0	18.7	23.0	25.3
5	CHURU	1970–2005	6.0	13.9	16.5	17.3
6	N. DELHI	1969–2005	11.2	13.7	17.0	18.1
7	BAREILLY	1970–2005	8.7	13.7	19.4	26.6
8	JAISALMER	1970–2005	5.8	9.2	9.6	12.9
9	JODHPUR	1971–2005	8.3	14.8	17.6	29.7
10	AJMER	1969–2005	8.0	17.2	24.2	26.6
11	JAIPUR	1969–2005	7.0	14.7	23.3	26.9
12	LUCKNOW	1969–2005	7.3	12.2	19.6	20.4
13	GORAKHPUR	1970–2004	8.0	16.4	19.4	21.1
14	GUWAHATI	1969–2006	8.5	16.3	17.9	18.6
15	ALLAHABAD	1969–2005	11.0	21.0	21.7	22.7
16	VARANASI	1970–2005	10.0	20.2	21.9	23.1
17	GUNA	1969–2003	13.4	16.1	21.6	25.1
18	SATNA	1969–2003	7.5	13.3	19.4	26.2
19	IMPHAL	1969–2000	6.0	9.2	10.4	11.5
20	BHUJ	1969–2003	9.4	13.0	17.2	22.5
21	AHMEDABAD	1969–2003	9.0	21.4	28.3	31.8
22	BHOPAL	1970–2004	9.0	13.2	17.2	28.1
23	JABALPUR	1969–2004	9.0	15.5	24.3	30.7
24	OKHA	1969–2003	13.5	22.2	25.6	27.6
25	RAJKOT	1969–2003	11.6	17.2	24.1	25.9
26	PORBANDAR	1969–2003	8.7	16.7	31.1	40.1
27	NAGPUR	1969–2005	7.9	16.3	21.8	25.8
28	JHARSUGUDA	1969–2006	9.0	14.1	17.4	19.4
29	VERAVAL	1969–2004	13.0	16.7	23.1	28.0
30	OZAR	1969–2005	8.1	17.1	18.1	18.5
31	BHUBANESHWAR	1969–2006	12.0	24.0	29.7	31.8
32	DAHANU	1973–2005	9.8	16.0	19.7	26.2
33	AURANGABAD	1969–2005	7.8	11.0	15.0	15.5
34	MUMBAI (COLABA)	1969–2004	11.3	25.0	39.4	49.6
35	PUNE	1969–2004	6.6	10.0	10.1	11.3
36	NIZAMABAD	1969–2004	6.0	12.1	20.2	31.4
37	RAMAGUNDAM	1969–2003	9.3	16.8	17.5	17.7
38	KALINGAPATNAM	1970–2004	9.9	18.4	21.0	25.1
39	RATNAGIRI	1971–2005	8.0	13.7	21.9	29.7
40	MAHABALESHWAR	1969–2005	7.1	11.5	19.7	31.9
41	SOLAPUR	1969–2005	7.0	10.1	11.1	14.0
42	HYDERABAD	1969–2003	10.0	24.1	34.3	36.5
43	GANNAVARAM	1969–2003	7.3	12.3	14.8	19.5
44	MACHILIPATNAM	1969–2003	9.0	16.0	19.7	24.3
45	KAKINADA	1969–2003	9.1	14.1	18.4	30.3
46	PANJIM	1969–2004	13.0	19.7	24.2	30.9
47	MORMUGAO	1969–2004	12.6	19.8	21.0	30.6
48	BELGAUM	1969–2003	7.7	11.4	12.2	12.5
49	GADAG	1969–2003	7.5	8.9	10.5	12.3
50	KURNOOL	1969–2003	7.1	13.7	13.9	13.9
51	ONGOLE	1970–2003	8.0	19.4	23.2	27.8
52	KARWAR	1974–2004	10.5	15.2	19.0	23.6
53	HONAVAR	1970–2004	9.8	14.2	19.5	26.2
54	CHITRADURG	1969–2003	7.5	8.9	9.8	12.0
55	ANANTAPUR	1969–2004	7.8	13.5	16.3	16.6
56	NELLORE	1969–2004	9.2	14.3	19.5	25.1
57	AGUMBE	1971–2003	8.9	16.0	24.2	32.0
58	MEENAMBAKKAM	1969–2005	8.7	13.0	18.9	25.3

Table I. (*Continued*).

Sr. no.	Station	Data period	Extreme rainfall (cm)			
			1 hr	3 hr	6 hr	12 hr
59	MANGALORE	1969–2004	9.3	13.2	16.5	23.6
60	BENGALURU	1969–2004	7.2	14.5	16.3	18.2
61	AMINI	1969–2002	9.0	14.7	21.3	27.5
62	CALICUT	1969–2003	8.7	12.9	18.4	24.1
63	COIMBATORE	1969–2005	7.6	14.4	15.3	16.6
64	CUDDALORE	1969–2005	7.7	12.8	17.4	28.8
65	PORT BLAIR	1969–2003	12.2	24.9	27.2	28.6
66	KODAIKANAL	1969–2005	10.0	13.3	13.3	16.4
67	TIRUCHIRAPALLI	1969–2005	9.6	15.5	17.4	26.7
68	KARAIKAL	1975–2005	7.4	14.4	24.5	30.9
69	NAGAPATTINAM	1969–2005	8.4	16.0	21.9	29.5
70	PAMBAN	1969–2005	8.0	11.9	15.1	20.5
71	MINICOY	1969–2002	8.0	17.8	23.4	26.3
72	THIRUVANANTAPURAM	1969–2003	7.7	17.5	20.0	23.6

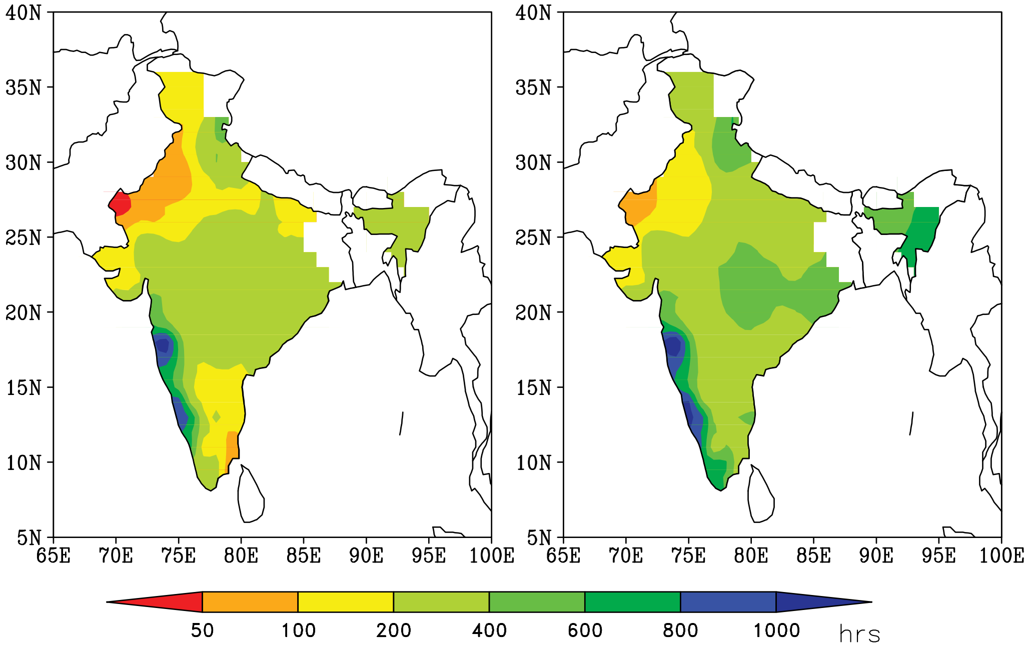

Figure 3. Average number of rain hours in summer monsoon season (left panel) and in a year (right panel) over India. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

change in the low rainfall events (<5 mm/h) but increase in the number of heavy rainfall events (>10 mm/h) in recent period. Figure 5 shows frequency distributions for some representative stations. X-axis indicates rainfall amounts (R) and Y-axis indicates frequency per year exceeding rainfall amount (R). Logarithmic scale for Y axis has been used in the plots to highlight the changes in the upper tail region of the curve. The same has been examined by carrying out trend analysis of number of heavy rainfall events (>10 mm/h) for all the stations. Figure 6 shows the trends in the number of heavy rainfall events (per year) and the stations showing significant change. It is clearly seen from the figure that, many stations in central India show increasing trends in the number of heavy rainfall events. The change is statistically significant at some stations (at 5 and 10% level of significance). The results are in good agreement with the findings of Goswami *et al*. (2006). They showed increase in the heavy rainfall events (>10 cm/day) over central India using the daily gridded rainfall data for the period 1951–2003.

5. Diurnal cycle of rainfall in India

Diurnal cycle of the rainfall at a place is defined here as the average distribution of hourly rainfall on a rain day (non-zero rainfall amount), representing a specified period of time, say a month or a season. It is generally

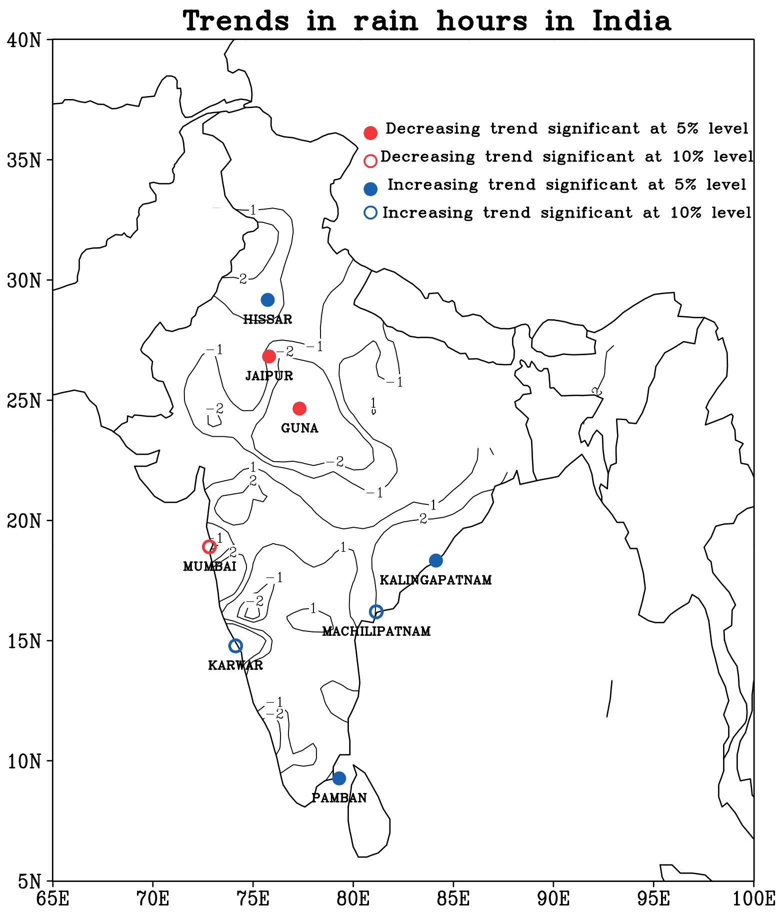

Figure 4. Mann-Kendall statistics in the number of rain hours during monsoon season. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

observed that the diurnal cycle of rainfall at individual station depends on the location of the station and on the season also. Pathan (1994) studied the diurnal cycle at some selected Indian stations during the southwest monsoon season. It is generally observed that at coastal and island stations the summer monsoon rainfall is characterized by enhanced rainfall activity from midnight to forenoon hours and decreased activity from afternoon to midnight hours. The inland stations show opposite behaviour with more rainfall during the afternoon and evening hours.

The present study examines the temporal changes in the diurnal cycle of rainfall during four seasons, namely, winter (January–February), pre-monsoon (March–May), summer monsoon (June–September) and post-monsoon (October–December), in different parts of the country. Seasonal diurnal cycles of rainfall have been estimated for all the stations and for reference and recent periods as mentioned earlier. These values are smoothed out by taking a 3-h running mean so as to reduce the noise in the series. Though the analysis has been carried out for all the 72 stations and for 4 seasons, diurnal cycle in the rainfall is discussed here for the main rainy season in different parts of the country with reference to selected 11 stations. Diurnal cycles of these 11 stations are shown in Figure 7. Figure 7 indicates that for Srinagar station located in northern India, morning and evening hours both contribute equally to the daily rainfall total. At this station, decrease in the rainfall intensity is observed in the pre-monsoon season in recent period. For Stations, Jaisalmer (northwest India), Jabalpur (central India), Bhuj (western part of the country) and Mahabaleshwar (a hill station in the Western Ghat at an altitude of 1372 m), rainfall activity is mainly restricted to summer monsoon season and rainfall peak in the diurnal cycle occurs in the afternoon/evening hours due to convective heating. At Mumbai, a station located along the west coast, rainfall occurs during monsoon season only. Diurnal cycle shows the rainfall maximum in late evening hours to early morning hours. This is due to interaction between sea breeze and land breeze which causes lifting of warm air from the sea by cold breeze from land causing rainfall in early morning hours. Substantial decrease has been observed, in the rain rate of morning hours of summer monsoon season at Mumbai in recent period. Mahabaleshwar shows an increased rainfall activity during the evening hours in the recent period. For Guwahati, a station in northeast India, morning hours contribute more to the daily rainfall total than afternoon hours during pre-monsoon as well as summer monsoon season. No perceptible change has been observed in the diurnal cycle at this station. At Kalingapatnam,

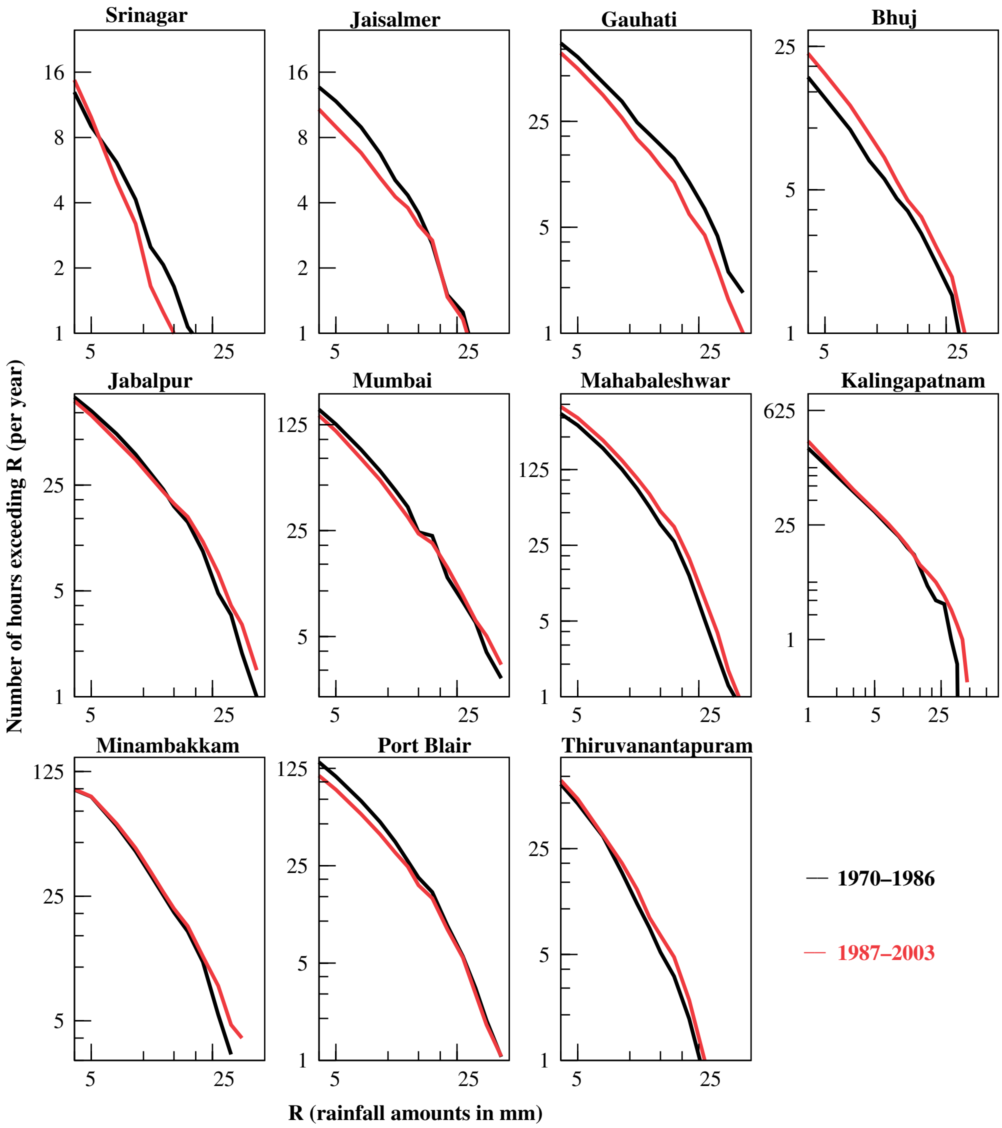

Figure 5. Frequency distributions of hourly rainfall events at 11 representative stations in India. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

situated on the east coast, rainfall occurs in summer monsoon and post-monsoon seasons. Afternoon hours in summer monsoon season show decrease in rainfall intensity, while increase in rainfall activity has been observed in post-monsoon season. For Meenambakkam, a station located on the southern part of east coast of India, morning and evening hours contribute to daily rainfall total in the summer monsoon season while all 24 h contribute to daily rainfall total during the post-monsoon season. No significant change is noticed in the rainfall activity in both the rainy seasons. For a coastal station Thiruvananthapuram, located in the southern parts of India, rainfall occurs in afternoon hours during pre-monsoon and post-monsoon seasons due to convective heating, and during summer monsoon season due to interaction between land and sea breeze. For the island station of Port Blair, located in the Bay of Bengal, rainfall activity is seen in all the seasons except the winter season, maximum being in the summer monsoon season. At this station, afternoon hours contribute more than morning hours. No temporal change has been observed at Port Blair.

6. Contribution of daytime rainfall to monsoon rainfall and its temporal variability

Analysis has been carried out to examine the temporal changes in daytime rainfall contribution to the monsoon seasonal rainfall total across India. It is observed that rainfall maximum during a rain day generally occurs in early morning hours over coastal stations, while over central parts of India, it occurs during afternoon or evening hours, so accordingly, daytime is considered here as 7 a.m. to 7 p.m., and nighttime as 7 p.m. to next day 7 a.m. For each of the 72 stations, yearly daytime rainfall totals (7 a.m. to 7 p.m.) during monsoon season and their percentage contribution to the monsoon seasonal totals have been estimated. Trend analysis of the

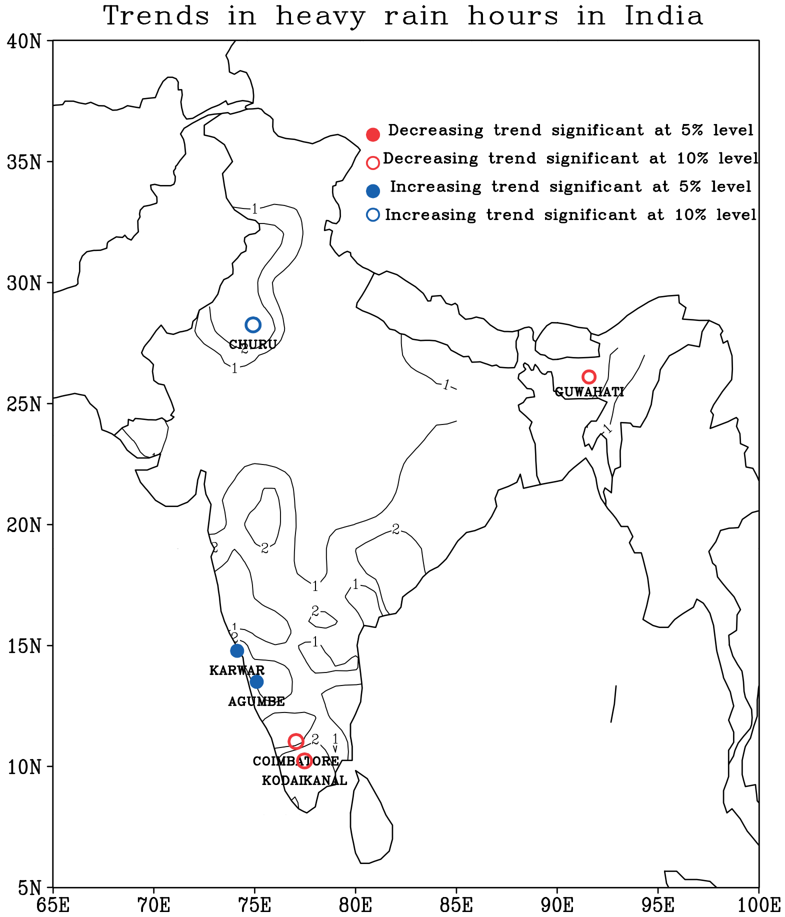

Figure 6. Mann-Kendall statistics in the number of heavy rain hours (>10 mm/h) during monsoon season. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

time series of daytime rainfall contribution is carried out using the Mann-Kendall test. Figure 8 shows (a) average contribution (%) of daytime rainfall to the monsoon rainfall total, and (b) trends in percentage contribution of daytime rainfall and stations showing significant change. Results for nighttime contribution can be derived from day time contribution so they are not shown here.

Figure 8(a) shows that over most parts of north-central India, daytime contribution to monsoon rainfall is more than 60%, while areas located along west and east coasts, in north and northeast India, and southeast peninsular India, nighttime contribution to monsoon rainfall is more. From Figure 8(b), it is clearly seen that many stations in India show decreasing trends in daytime contribution to monsoon rainfall (statistically significant at 5% level of significant at a few stations).

7. Extreme rainfall of durations less than 12 h

7.1. Highest recorded hourly rainfall

Highest ever recorded rainfall amount for durations such as 1, 3, 6, and 12 h were calculated for all 72 stations. These values are given in Table I. Figure 9 depicts the spatial patterns of these extreme rainfall amounts.

It is seen that most of the stations over the west coast receive 10 cm or more rainfall in 1 h. Stations near east coast located along the monsoon trough region, and some stations at the foothills of the Himalayas have also recorded extreme rainfall of 10 cm or more in 1 h. From Table I, it is noted that the station Okha, located on northern part of west coast, received 13.48 cm in a 1-h duration on 10 July 1973. Such heavy rainfall activity was associated with a cyclonic circulation formed over the Arabian Sea and simultaneous occurrence of low pressure area over central India. Stations in peninsular India that lie in the rain-shadow region of the Western Ghats have never recorded more than 8 cm of rainfall in 1 h. Highest rainfall for the duration of 3–6 h, over India, ranges from 14 cm to more than 20 cm, except for the rain-shadow region of peninsular India and northwest India. Rainfall amount corresponding to a 12-h duration exceeds 40 cm at some places along the west coast stations. Such maps give an idea of the spatial variation of rainfall intensity in India and can provide important information in flood control studies.

7.2. Trends in the extreme rainfall amounts in short durations (<12 h)

Long-term trends in the extreme rainfall time series of different durations (such as 1, 3, 6, and 12 h) have been examined. The Mann-Kendall test has been employed to annual extreme rainfall series of different durations at stations possesing consistent data period of 1970–2003.

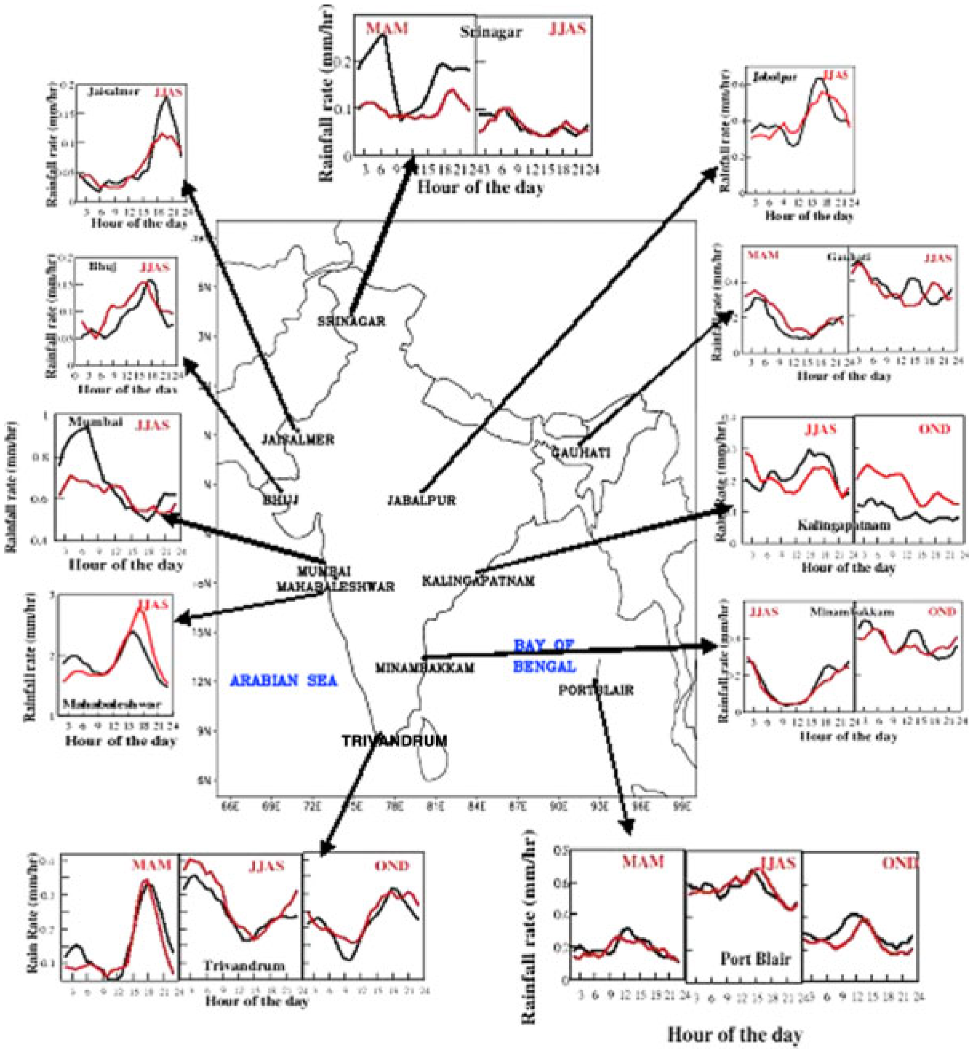

Figure 7. Diurnal cycle of rainfall during chief rainy season for 11 representative stations over different parts of India for the period 1970–1986 (black lines) and 1987–2003 (grey lines). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

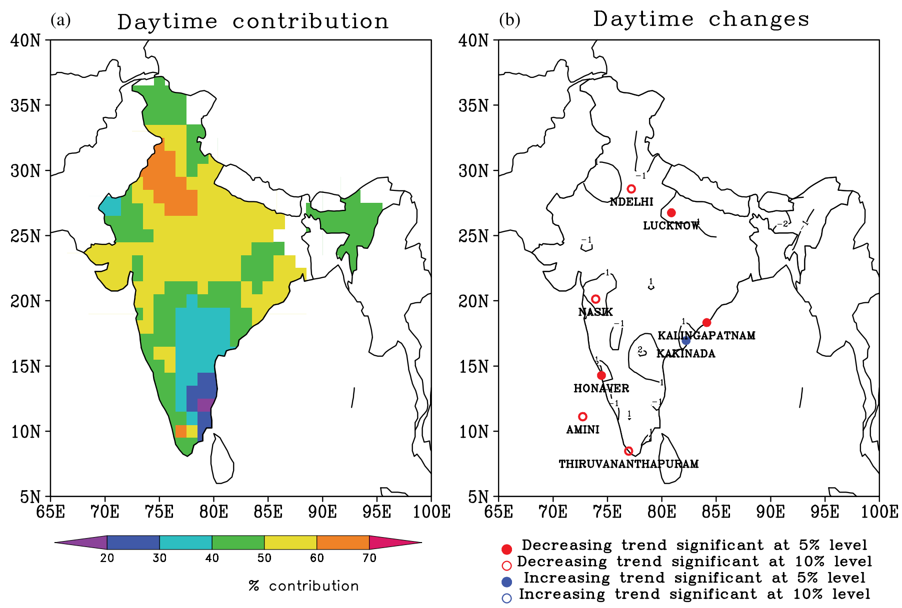

Figure 8. (a) Average daytime Contribution, and (b) Mann-Kendall statistics in daytime contributions to monsoon rainfall. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

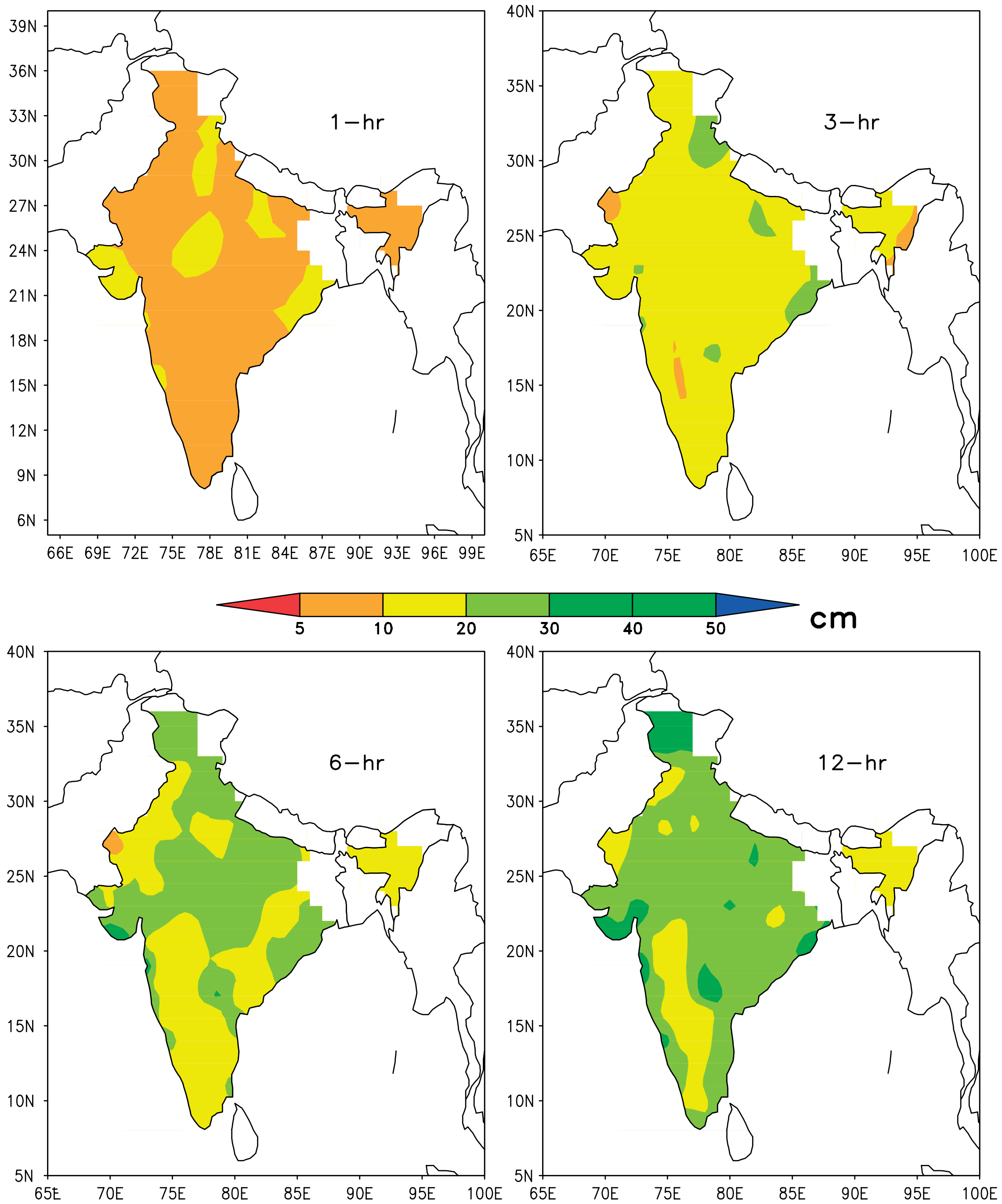

Figure 9. Spatial Patterns of extreme rainfall amounts (cm) for the duration of 1, 3, 6, 12 h. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Figure 10 shows trends in the extreme rainfall. Stations showing significant change at 5 and 10% level of significance are marked on the map. Over most parts of India, except northeast India and some isolated pockets in central and southern peninsular regions, extreme rainfall amounts of short duration are increasing, and at some stations this change is statistically significant at 5% level. These results are in good agreement with the results of trend analysis in extreme hourly rainfall by Sen Roy (2009). Increase in heavy rainfall events based on daily rainfall data, over the central part of India, has also been shown by Goswami *et al*. (2006).

8. Time distribution of heavy rain spells of 24-h duration

Probable Maximum Precipitation is an important component in designing major hydraulic structures (WMO, 1986). It is an estimate of the physical upper limit for the rainfall amount, at a place for a given duration of time, derived from long-period daily rainfall data. It is essential in hydrometeorology, to know about the distribution of rainfall during a heavy rain spell of 24-h duration at a place. Many studies available in India pertain to a part of a river basin or entire river basin. The

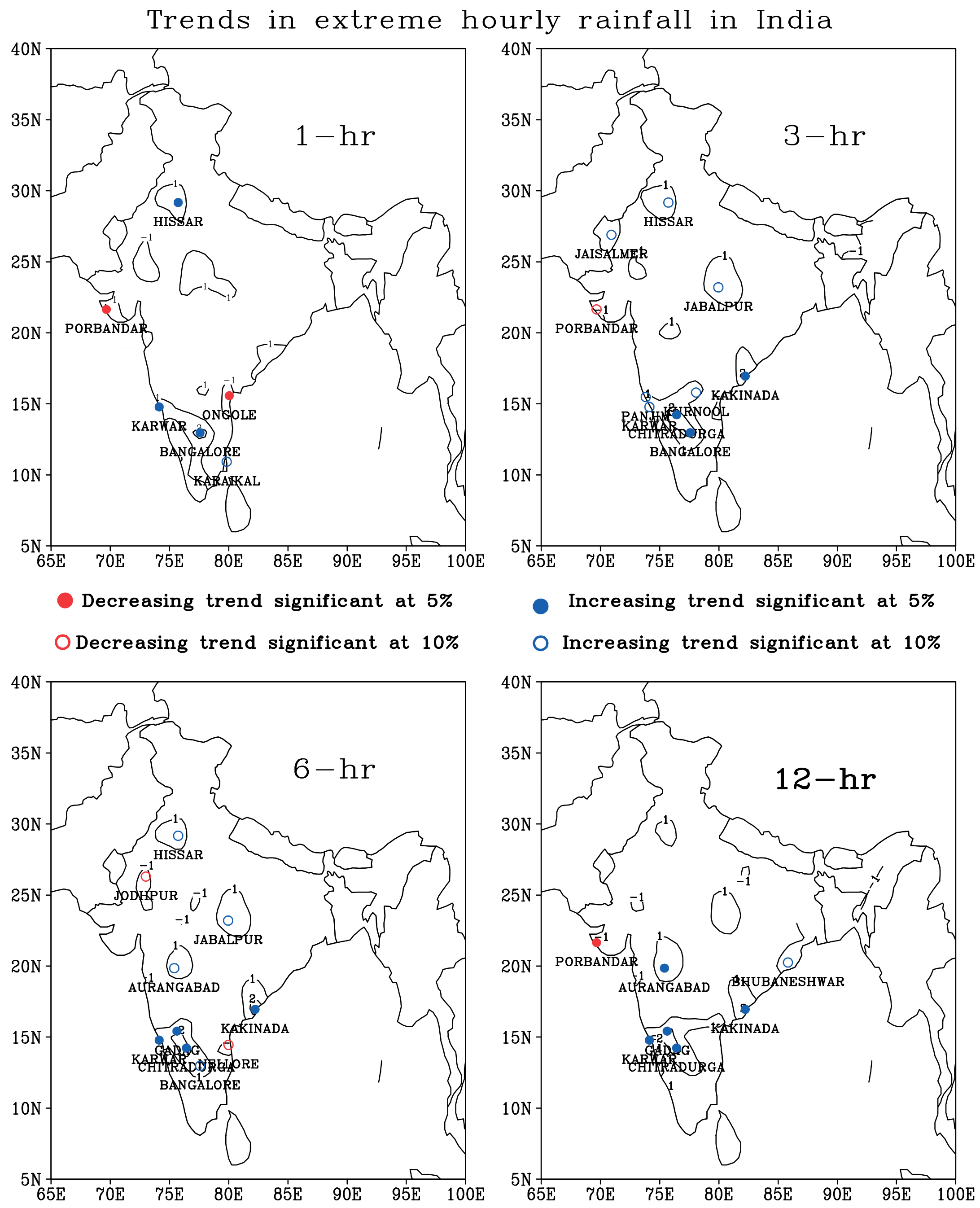

Figure 10. Mann-Kendall statistics in short duration (<12 h) extreme rainfall over India. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

present study gives the overall time distribution of rainfall across India. Estimation of time distribution involves the selection of heavy rain spells. The following criterion has been adopted for the selection of heavy rain spells at a station for carrying out the time distribution analysis:

A heavy rain spell is defined here, as the continuous rainfall process (all hours with positive rainfall amount) and total rainfall during the rain spell exceeding a certain threshold. Here the threshold has been taken as the 10% of the seasonal rainfall at a place. It is observed that for some stations in arid or semiarid region in India, there are very few rain spells of continuous 24 h rainfall. In such cases, to carry out time distribution, condition of every hour with positive rainfall is relaxed, and 1–2 h of zero rainfall are allowed within a rain spell. The three most severe rain spells of 24-h duration are then chosen for each of the 72 stations. For each of these rain spells, percentage contribution of 1, 3, ... 18 h rainfall to 24 h rainfall is calculated. Average time distribution is then obtained by averaging the percentage contribution of 3 selected heavy rain spells at a station. Figure 11 shows the spatial patterns of average percentage contributions from 3, 6, 12, and 18 h to the rainfall total of 24 h, during heavy rain spells. Figure 11 indicates contribution from intense 3-h rainfall ranges from 20–40% in

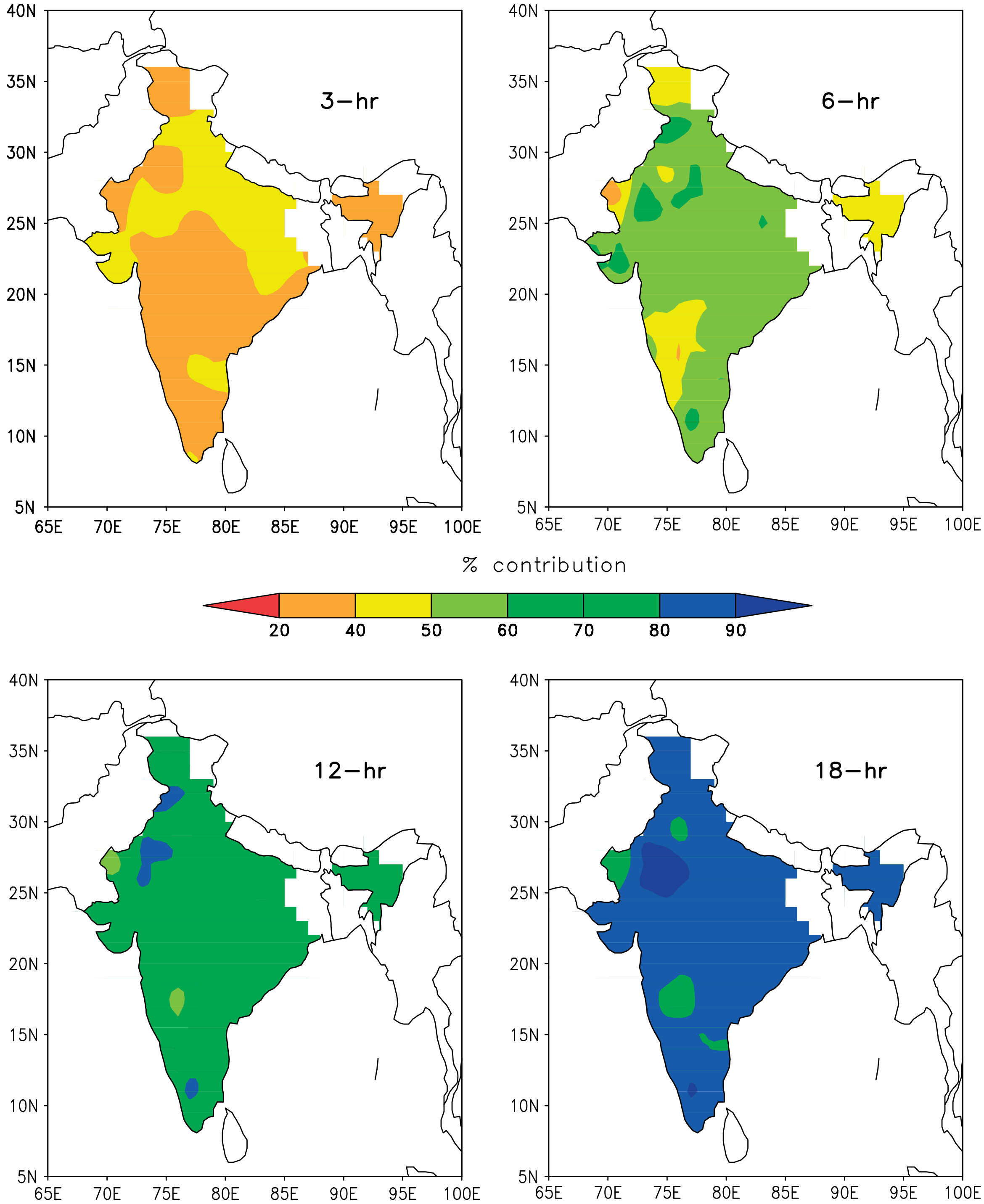

Figure 11. Spatial patterns of rainfall contributions from different hours (in percentage) during heavy rain spell of 24-h duration. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

peninsular India, and 40–50% in northern India. 50–60% contribution comes from a 6-h duration of intense rainfall over most parts of India, except northeast India and some pockets in northern and peninsular India, while 12 h contribution ranges from 70 to 80% at many places in India which shows the spatial variability in the rainfall patterns over different regions in India. It also indicates that, nearly three-fourth of the daily rainfall occurs in 12 h and the remaining one-fourth is contributed by the other 12 h. Such information is required for water management of reservoirs in different river basins.

9. Summary and conclusions

The present study provides a comprehensive assessment of the characteristics of the hourly rainfall over India based on a large network of SRRG stations with data availability exceeding 25 years. Such analysis is very useful for the design of various hydraulic structures, managenment of water resources in different river basins in the country. We believe the characterisation of diurnal cycle in the rainfall across the country can act as a bench mark for the validation of global and regional climate models (coupled and non-coupled) in their ability to capture this very important aspect having implications on the simulated regional and global climate. Temporal changes in various indices representing different hydroclimatic aspects have been assessed in the light of changing climate due to global warming. We recognize that the lack of the uniformity in the available data and its length could affect the results to some extent, but enough care was exercised while making useful conclusions. Accuracy in the results will definitely increase with the data availablity for sufficiently long period. The major conclusions of the study are:

1. Number of rain hours contributing to the annual rainfall total is highest along the west coast region, while it is found to be minimum over northwest India. Over most of the peninsular India, number of rain hours shows an increasing trend, while a decrease in the number of rain hours is observed over north-central and northeast India. At some places along the east coast the increase is statistically significant at 5% level.
2. Many places in India show an increasing tendency in the frequency of extreme hourly rainfall events (>10 mm/h) except for a few stations in northeast India and south peninsula.
3. No significant change has been observed in the diurnal cycle of rainfall during the monsoon season in recent period (1987 onwards) excepting a few stations located in central and western parts of India.
4. Most of north-central India receives more than 60% of monsoon rainfall during daytime, while areas located along west and east coasts, north and northeast India and southeast peninsular India, nighttime contribution to monsoon rainfall is more. Daytime contribution to monsoon rainfall is decreasing at many places in india. At some stations this decrease is statistically significant at 5% level.
5. Rainfall amount of the order of 10 cm and more has been recorded in an hour at stations along the west coast, along the tracks of monsoon disturbances and also along the foothills of the Himalayas. Extreme rainfall amounts of shorter durations (<12 h) are increasing at many places in the country.
6. Time distribution of heavy rainspells of 24-h duration indicate that 3 h of intense rainfall can contribute 20–40% to daily rainfall in peninsular India and about 40–50% in northern India. A contribution of 50–60% comes from a 6-h duration of intense rainfall over most parts of India, except northeast India and some pockets in northern and peninsular India. Nearly three-fourth of the daily rainfall occurs in 12 h duration, and one-fourth is contributed by the remaining 12 h.

Decrease in the number of rain hours in central India may be due to substantial weakening of meridional Sea Surface Temperature (SST) gradient during summer and therefore resulting into weakening of monsoon circulation and, thus, reduction in monsoon rainfall at most of the places in central India (Chung and Ramnathan, 2006). It has been shown by Rajeevan *et al*. (2008) that surface water vapour content and surface mean wind speeds are increasing significantly over the ocean during monsoon season causing increase in the evaporation flux from the ocean surface and more moisture availability, and this may result in an increase in the number of extreme events.

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