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RESEARCH ARTICLE

Statistical characteristics of cloud burst and mini-cloud burst events during monsoon season in India

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A short-duration heavy rainfall events over India have been studied using hourly rainfall data of 126 stations for the period 1969–2015 for the Indian summer monsoon season. The events have been classified into two categories. The first category pertains to cloud burst (CB). The CB events have been further classified into two types, viz. "CBa" and "CBb." CBa events are associated with heavy rainfall in the steep slope mountainous regions of Himalayas identified based on flash floods and damages to properties and human losses, irrespective of the rainfall amount. CBb events are associated with rainfall >10 cm/hr as per the definition by India Meteorological Department (IMD). The statistics of CBb events has been provided in the paper. A total of 28 CBb events have been recorded over Indian region in the study period. These are found to occur over different parts of India. A new and second category of short-term heavy rainfall event has been defined as "mini-cloud burst" (MCB). It is an event in which rainfall in two consecutive rain-hours is 5 cm or more. Statistical characteristics of these events have been investigated. MCB occurs in June over Western Ghats, over central India and foot hills of Himalayas in July and August. The frequency is low in the month of September. These events generally found to occur in the early morning hours at foot hills of Himalaya and along the west coast of India. In the interior of the land mass these are observed in the afternoon hours while in southern peninsula during night hours. Trend analyses indicate significant increase in these events at many places, except over northeast India. The statistics of CBb and MCB events provided in the paper will trigger numerical modelling studies for understanding the dynamics and invigoration of convection.

KEYWORDS
cloud burst events, mini-cloud burst events, short-duration heavy rainfall events

1 | INTRODUCTION

On 24-hr timescale, intensity of rainfall has been classified as heavy (>6.5 cm/day), very heavy (>13.0 cm/day) and extremely heavy (>20.0 cm/day) by India Meteorological Department (IMD). The intensity of rainfall has a further category for a short-period violent downpour over a limited area called as a cloud burst (CB). Characteristics of their spottiness and relatively high intensity suggest the bursting and discharge of a whole cloud water at once. CBs are usually associated with deep convective clouds/thunderstorms. One of the oldest references on the CB studies goes back to Woolley (1946) who investigated CB-associated floods in Utah, United States which occurred during the period 1850–1938 using the information from the newspaper reports available at that time. In India such events are commonly seen in the hilly and mountainous regions of Himalayas. Because of very small spatial and temporal scales, these are not captured by the coarse rain gauge network of IMD. Their occurrences have been inferred from the flash floods and associated damages. Dimri *et al*. (2017) presented a review of the CB studies in the western Himalaya. They reported that most of the CB events occurred in the elevation range of 1,000–2,500 m within the valley folds of the southern rim of the Indian Himalaya. They concluded that CB occurs during the monsoon season due to strong convection associated with orographic forcing over the Himalaya. Associated convection in the form of cumulonimbus clouds shoot up to 15 km in the vertical. As per IMD, a CB event is defined when rainfall at a place exceeds 10 cm in 1 hr. If one goes by stringent IMD definition, many of the CB events in Himalayas will not be qualified to call as CB events. So it prompts a necessity to redefine the CB event. With this view, CB events are redefined to accommodate past studied Himalayan region CB events and those which qualify as per IMD definition. The statistics of CB events has been provided in the paper.

On many occasions, rainfall of 5 cm and above occurs within 2 hr. Such events do not fall under the category of CB event. The flood and damage potentials of such events are of similar type albeit at lower intensity than CB events. At present existence of such events remained obscured in the meteorological community. We coin the term mini-cloud bursts (MCB) to identify these intermediate-scale rainfall intensity events. The term MCB has been used first by Ramage and Schroeder (1999) in connection with high rainfall associated with Mount Waialeale, Kauai. However, they did not give a quantitative definition of MCB. Taking concept from their study, we define MCB as rainfall event in which rainfall in consecutive two rain-hours (with positive rain amount) exceeds 5 cm at a place. Rainfall >5 cm in 2 hr is indicative of torrential rainfall similar to CB but of lesser intensity, hence the term MCB. The reason for considering rainfall threshold of 5 cm in 2 hr is follows. The extreme rainfall is identified by IMD when the rainfall is 20 cm in 24 hr which amounts to 1.6 cm in 2 hr. The run-off of the water and flash floods occurs when the rate of accumulation of water exceeds absorption of the water. When the rainfall intensity is more than 5 cm/2 hr that is in MCB event, the rate of accumulation of water is more than three times than that in the extreme rainfall event. The probability of flash floods is three times higher in the MCB than in extreme rainfall event. The intensity of rainfall at the threshold value is well above the intensity of rainfall in the extreme rainfall event however below the rainfall intensity in CB event. The number of rainfall events reduces drastically when the threshold is increased above 5 cm (shown in the section 3). Another problem with recording of CB event is that high rainfall do not necessarily occur within the 60 min of clock hour but may spill over 60 min in two adjacent hours. Our rainfall recording system is tied with clock hour observation. In such cases, it may not get recorded as a CB event. Averaging rainfall for 2 hr reduces this type of eventuality and brings out existence MCB event.

MCB are not confined to hilly areas, but occur at many places. Their integrated impact may be similar to CB event High probability of getting these events captured by the observing stations, makes it possible to study these events. With this view, the statistical analysis of MCB events has been carried out. With increase in global warming, studies report that the hydrological cycle is likely to be intensified. Goswami *et al*. (2006) showed that there has been an increase in extreme rainfall events in the monsoon season over central India. Rajeevan *et al*. (2008) studied the variability and trends in the extreme rainfall events using 104 years daily gridded rainfall data in India and showed that the increasing trend of extreme rainfall events in the last five decades could be associated with the increasing trend in the sea surface temperatures and surface latent heat flux over the tropical Indian Ocean. However, Ajayamohan *et al*. (2010) showed that increasing frequency of extreme rainfall events in India are likely to be attributable to the rising trends in the synoptic activity. Further they added that this increase in synoptic activity results from a rising trend in relatively weak low-pressure systems (LPS), and a declining trend in stronger LPS.

Trend analysis and quantile plot (QQ plots) technique have been used to examine the temporal changes in the MCB events.

2 | DATA

Hourly rainfall data of 126 self recording rain gauge (SRRG) stations in India for the period 1969–2015 (with variable data length but at least 75% data availability during the monsoon season June–September for each year) have been used in the analysis. The data has been quality controlled by standard methods. Table 1 gives the names of the stations along with the geographical co-ordinates, subdivision and state where they are located. For the meteorological purposes, India is divided into 36 subdivisions. Figure 1 shows the map of India with 36 subdivisions (www.tropmet.res.in). Figure 2 shows locations of 126 SRRG stations and the topographical features. Data availability of these stations with starting and ending years of observation are shown in Figure 3. It is seen from Figures 2 and 3 that SRRG stations have well distribution over India and have sufficient long period of hourly rainfall data to draw the statistical inferences about CB and MCB events. Maximum data of 47 years (1969–2015) are available for the stations Bhubaneshwar located on the east coast of India, in Odisha subdivision and Kodaicanal located in the Tamilnadu subdivision. As high as 65 stations, have data periods of 40 years or more. Very few stations have data period around 15 years. But due to their importance of geographical locations they have been considered in the analysis to draw inferences.

3 | RESULTS AND DISCUSSIONS

3.1 | Spatial distribution

3.1.1 | CB events

IMD defines CB event as an event in which rainfall >10 cm occurs in 1 hr. A large number of studies have been carried out regarding CB events over Himalayan region

TABLE 1 List of station, geographical co-ordinates, subdivision and state

No.	Station name	Lat	Lon	Subdivision	State	No.	Station name	Lat	Lon	Subdivision	State
1	Gulmarg	34.05	74.4	Jammu.Kashmir	Jammu.Kashmir	32	Gorakhpur	26.75	83.37	East UP	Uttar Pradesh
2	Srinagar	34.08	74.83	Jammu.Kashmir	Jammu.Kashmir	33	Guwahati	26.01	91.58	Assam-Meghalay	Assam
3	Dharamsala	32.27	76.38	H.P.	Himachal Pradesh	34	Barmer	25.75	71.38	West Rajasthan	Rajasthan
4	Amritsar	31.63	74.87	Punjab	Punjab	35	Allahabad	26.45	81.73	East UP	Uttar Pradesh
5	Simla	31.13	77.17	H.P.	Himachal Pradesh	36	Varanasi	25.45	82.87	East UP	Uttar Pradesh
6	Ferozpur	30.91	74.66	Punjab	Punjab	37	Patna	25.6	85.17	Bihar	Bihar
7	Patiala	30.33	76.47	Punjab	Punjab	38	Shillong	25.57	91.88	Assam-Meghalay	Meghalay
8	Ambala	30.4	76.77	Haryana	Haryana	39	Guna	24.65	77.32	West MP	Madhya Pradesh
9	Dehradun	30.32	78.03	Uttarakhand	Uttarakhand	40	Satna	24.57	80.83	East MP	Madhya Pradesh
10	Yehri	30.4	78.49	Uttarakhand	Uttarakhand	41	Gaya	24.75	84.95	Bihar	Bihar
11	Sriganganagar	29.92	73.92	West Rajasthan	Rajasthan	42	Silchar	24.75	92.8	Assam-Meghalay	Meghalay
12	Hissar	29.17	75.73	Haryana	Haryana	43	Imphal	24.77	93.9	Nag.mani.mizo.trip	Manipur
13	Karnal	29.7	77.03	Haryana	Haryana	44	Naliya	23.25	68.85	Saurashtra-Kutch	Gujrath
14	Merrut	29.02	77.05	West UP	Uttar Pradesh	45	Bhuj	23.25	69.67	Saurashtra-Kutch	Gujrath
15	Mukteswar	29.47	79.05	Uttarakhand	Uttarakhand	46	Ahmedabad	23.07	72.63	Gujrath	Gujrath
16	Churu	28.25	74.92	West Rajasthan	Rajasthan	47	Bhopal	23.17	77.21	West MP	Madhya Pradesh
17	N. Delhi(Safdar)	28.58	77.2	Haryana	Haryana	48	Jabalpur	23.2	79.95	East MP	Madhya Pradesh
18	Moradabad	28.8	78.75	West UP	Uttar Pradesh	49	Bankura	23.38	87.07	Gangetic WB	West Bengal
19	Bareilly	28.37	79.4	West UP	Uttar Pradesh	50	Shantiniketan	23.05	87.7	Gangetic WB	West Bengal
20	Tadong	27.33	88.63	Sikkim	Sikkim	51	Agartala	23.88	91.25	Nag.mani.mizo.trip	Tripura
21	Shahjahanpur	27.89	79.9	West UP	Uttar Pradesh	52	Okha	22.48	69.12	Saurashtra.Kutch	Gujrath
22	Bahraich	27.57	81.6	East UP	Uttar Pradesh	53	Dwarka	22.37	69.08	Saurashtra.Kutch	Gujrath
23	N. Lakhimpur	27.23	94.12	Assam-Meghalay	Assam	54	Rajkot	22.3	70.78	Saurashtra.Kutch	Gujrath
24	Dibrugarh	27.48	95.02	Assam-Meghalay	Assam	55	Indore	22.72	75.8	West MP	Madhya Pradesh
25	Jaisalmer	26.9	70.92	West Rajasthan	Rajastahn	56	Pendra.Rd	22.77	81.9	Chattisgarh	Chattigarh
26	Jodhapur	26.3	73	West Rajastha	Rajastahn	57	Kolkata	22.53	88.33	Gangetic WB	West Bengal
27	Ajmer	26.45	74.62	East Rajasthan	Rajastahn	58	Diamond.harbour	22.18	88.2	Gangetic WB	West bengal
28	jaipur(Sanganer)	26.82	75.8	East Rajasthan	Rajastahn	59	Porbandar	21.65	69.67	Saurashtra.Kutch	Gujrath
29	Gwalior	26.23	78.25	West MP	Madhya Pradesh	60	Bhaunagar	21.75	72.2	Saurashtra.Kutch	Gujrath
30	Lucknow	26.75	80.88	East UP	Uttar Pradesh	61	Nagpur	21.1	79.05	Vidarbha	Maharashtra
31	Sultanpur	26.33	82.17	East UP	Uttar Pradesh	62	Raipur	21.22	81.67	Chattisgarh	Chattisgarh
63	Jharsuguda	21.92	84.08	Odisha	Odisha	95	Gadag	15.42	75.63	N. Int Karnataka	Karnataka
64	Digha	21.83	87.78	Gangetic WB	West Bengal	96	Bellary	15.15	76.85	S. Int Karnataka	Karnataka
65	Veraval	20.9	70.37	Saurashtra-Kutch	Gujrath	97	Kurnool	15.8	78.7	Coastal AP	Andhra Pradesh
66	Nasik	20.13	73.92	Madhya Maharashtra	Maharashtra	98	Baptala	15.9	80.47	Coastal AP	Andhra Pradesh
67	Akola	20.7	77.07	Vidarbha	Maharashtra	99	Ongole	15.57	80.05	Coastal AP	Andhra Pradesh
68	Kanker	20.27	81.48	Chattisgarh	Chattisgarh	100	Karwar	14.78	74.13	Coastal Karnataka	Karnataka
69	Bhubaneshwar	20.25	85.83	Odisha	Odisha	101	Honavar	14.28	74.45	Coastal Karnataka	Karnataka
70	Dahanu	19.97	72.72	Konkan	Maharashtra	102	Chitradurga	14.23	76.43	S. Int Karnataka	Karnataka
71	Chikhalthana	19.85	75.4	Marathwada	Maharashtra	103	Anantpur	14.68	77.62	Rayalseema	Andhra Pradesh
72	Jagdalpur	19.08	82.03	Chattisgarh	Chattisgarh	104	Kavali	14.9	79.98	Coastal AP	Andhra Pradesh
73	Puri	19.8	85.82	Odisha	Odisha	105	Nellore	14.45	79.98	Coastal AP	Andhra Pradesh
74	Mumbai(Colaba)	18.9	72.82	Konkan	Maharashtra	106	Agumbe	13.5	75.1	S. Int Karnataka	Karnataka
75	Pune	18.53	73.85	Madhya Maharashtra	Maharashtra	107	Shimoga	13.91	75.62	S. Int Karnataka	Karnataka
76	Nizamabad	18.67	78.1	Telangana	Telangana	108	Nungambakkam	13.7	80.25	Tamilnadu	Tamilnadu
77	Ramgundam	18.77	79.43	Telangana	Telangana	109	Minambakkam	13	80.18	Tamilnadu	Tamilnadu
78	Kalingapatnam	18.33	84.13	Coastal AP	Andhra Pradesh	110	Mangalore	12.92	74.88	Coastal Karnataka	Karnataka
79	Ratnagiri	16.98	73.33	Konkan	Maharashtra	111	Bangalore	12.97	77.58	S. Int. Karnataka	Karnataka
80	Mahabaleshwar	17.93	73.67	Madhya Maharashtra	Maharashtra	112	Aminidivi	11.12	72.73	Island In Arabian Sea	Island
81	Solapur	17.67	75.9	Madhya Maharashtra	Maharashtra	113	Kozhikode	11.25	75.78	Kerala	Kerala
82	Hyderabad	17.45	78.47	Telangana	Telangana	114	Coimbatore	11.03	77.05	Tamil Nadu	Tamil Nadu

TABLE 1 (Continued)

No.	Station name	Lat	Lon	Subdivision	State	No.	Station name	Lat	Lon	Subdivision	State
83	Khammam	17.25	80.15	Telangana	Telangana	115	Cuddalore	11.77	79.77	Tamil Nadu	Tamil Nadu
84	Tuni	17.35	82.55	Coastal AP	Andhra Pradesh	116	Pondicherry	11.97	79.82	Pondicherry	Pondicherry
85	Vishakhapatnam	17.72	83.3	Coastal AP	Andhra Pradesh	117	Portblair	11.67	92.72	Island in Bay Of Bengal	Island
86	Kolhapur	16.7	74.21	Madhya Maharashtra	Maharashtra	118	Kodaikanal	10.23	77.47	Tamil Nadu	Tamil Nadu
87	Raichur	16.2	77.35	N. Int Karnataka	Karnataka	119	Tiruchirapalli	10.77	78.72	Tamil Nadu	Tamil Nadu
88	Gannavaram	16.53	80.8	Coastal AP	Andhra Pradesh	120	Karaikal	10.92	79.83	Pondicherry	Pondicherry
89	Machilipatnam	16.2	81.15	Coastal AP	Andhra Pradesh	121	Nagapattinam	10.77	79.85	Tamil Nadu	Tamil Nadu
90	Narsapur	16.43	81.7	Telangana	Telangana	122	Adirampattinam	10.33	79.38	Tamil Nadu	Tamil Nadu
91	Kakinada	16.95	82.23	Coastal AP	Andhra Pradesh	123	Tondi	9.73	79.03	Tamil Nadu	Tamil Nadu
92	Panjim	15.48	73.82	Goa	Goa	124	Pamban	9.27	79.3	Tamil Nadu	Tamil Nadu
93	Mormugao	15.42	73.78	Goa	Goa	125	Minicoy	8.3	73.15	Island In Arabian Sea	Island
94	Belgaum	15.85	74.62	N. Int Karnataka	Karnataka	126	Thiruvanantpuram	8.48	76.95	Kerala	Kerala

(Dimri *et al.,* 2017, and references therein). Non-availability of rain gauge stations at the locations of CB events, the rainfalls have been estimated using Tropical Rainfall Measuring Mission (TRMM) data for 3-hr period. It is known that TRMM rainfall estimates are having a large uncertainties in mountainous regions. Moreover, the rainfall estimates from TRMM fall short of required threshold value as defined by IMD. For example, rainfalls at Gona Tehri on August 31, 2001 was 22 mm/hr, Leh Ladakh August 6, 2010 was 23.3 mm/hr, Badrinath June 16–17, 2013 was 25 mm/hr (from Dimri *et al.,* 2017, tables 1 and 2). Woolley (1946) called short heavy rainfall events over the steep mountain as CB events. The mountainous topography and steep slope allow rainwater to get collected with high speed resulting in to flash floods. The high flow rate of the water causes damages to the properties, roads, trees, etc. Traditionally short-

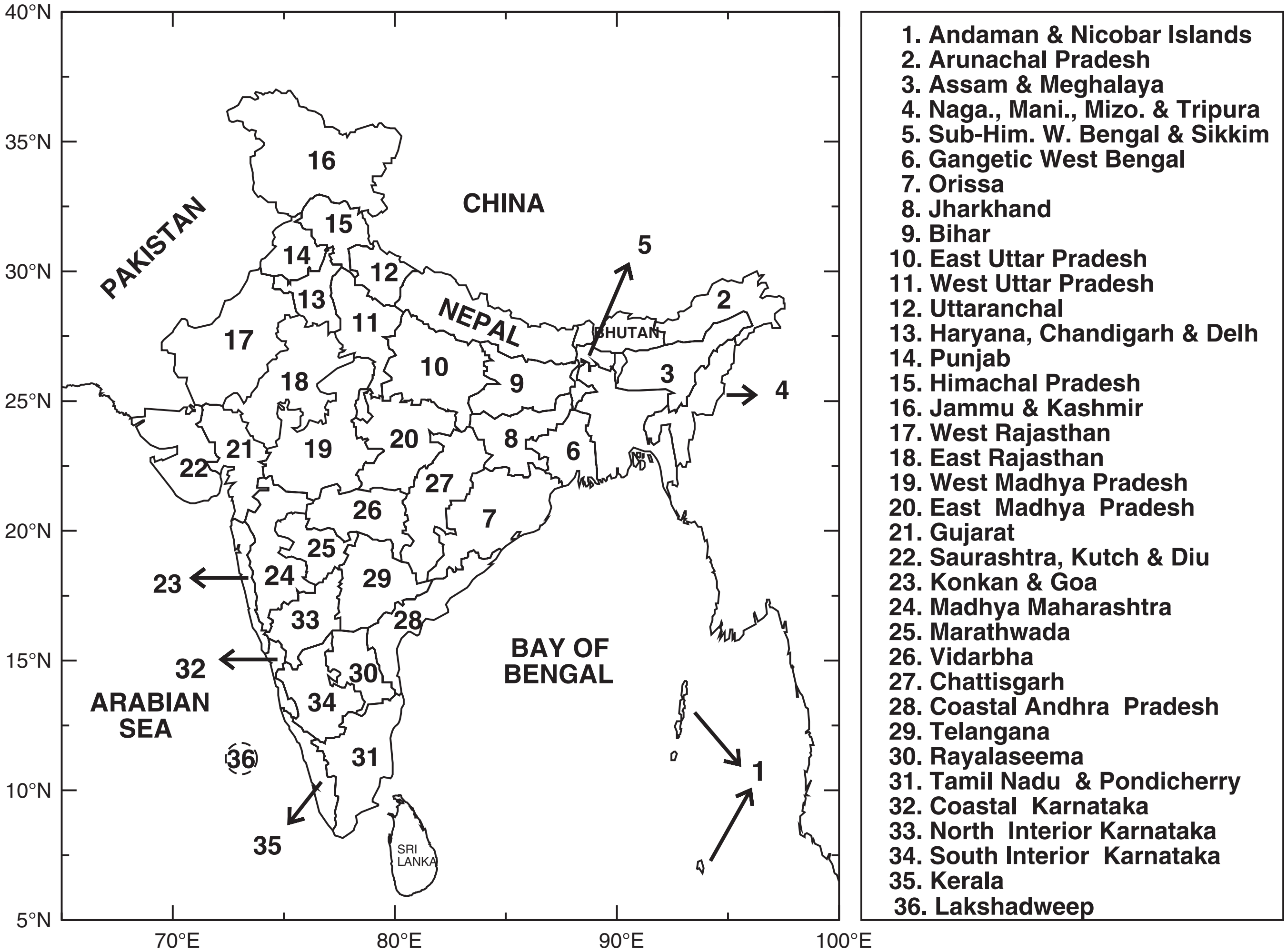

FIGURE 1 Meteorological subdivisions of India

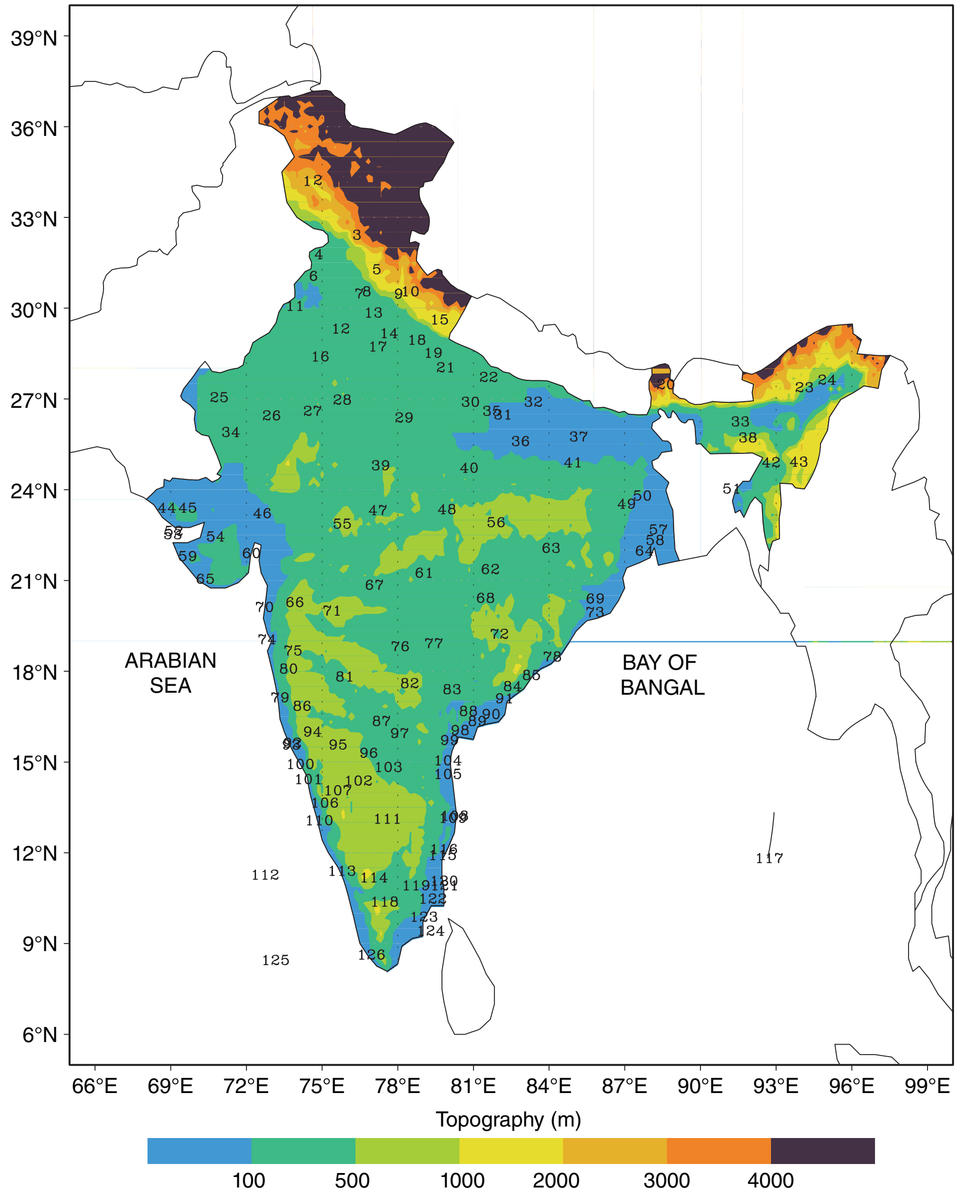

FIGURE 2 Locations of stations with topographical features [Colour figure can be viewed at wileyonlinelibrary.com]

duration heavy rainfall events causing flash floods and damages to properties in the Himalayan region have been called as CB events. Conceptually, this is in agreement with Woolley (1946). Considering these two facts, we redefine and categorize CB events into two types. Type "CBa" short-duration heavy rainfall events occurring in the Himalayan

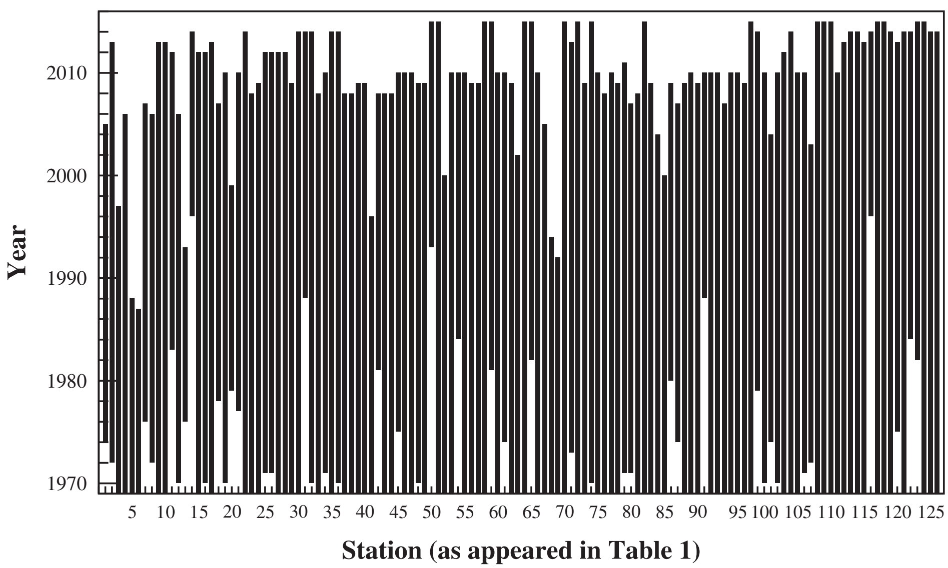

FIGURE 3 Data availability of 126 stations (starting and ending year)

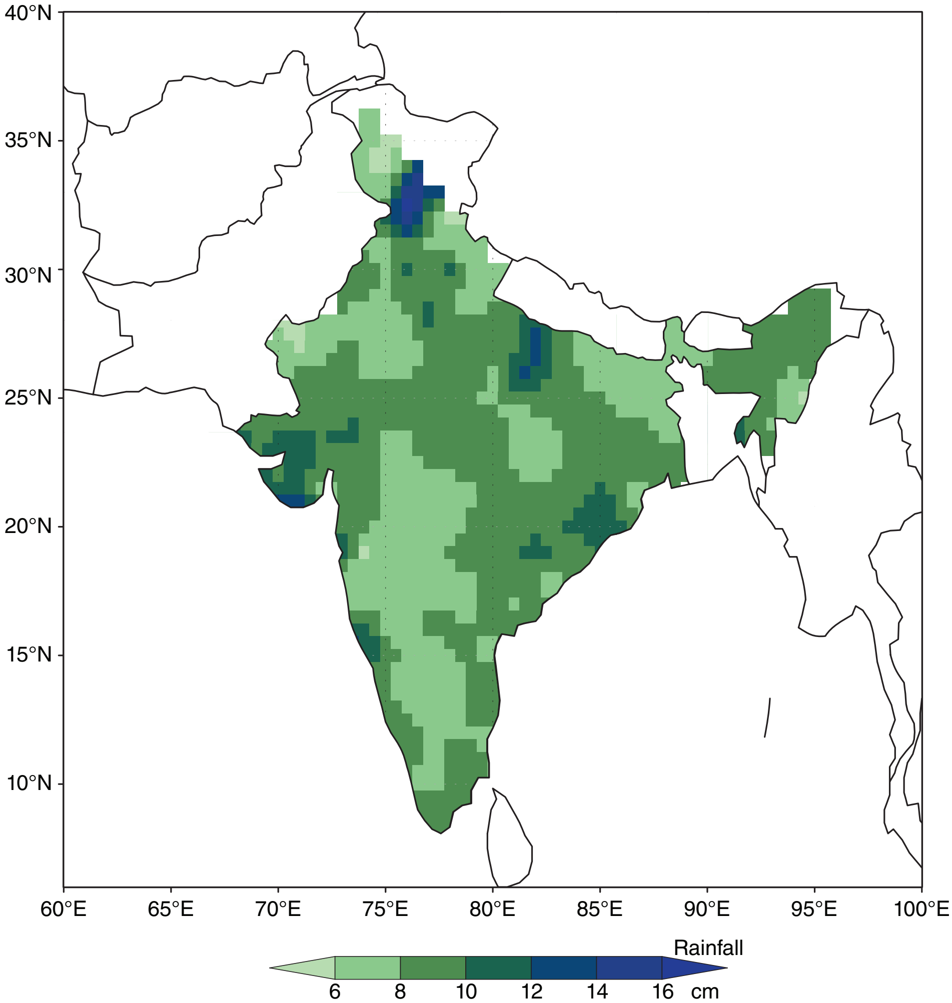

FIGURE 4 Spatial pattern of extreme 1-hr rainfall (cm) [Colour figure can be viewed at wileyonlinelibrary.com]

steep slopes regions resulting in to flash floods and causing heavy damages to the properties, consistent with the current practices and Woolley (1946) concepts. Type "CBb": short-duration heavy rainfall events with rainfall >10 cm in 1 hr as per IMD definition. This new definition is more wider and encompasses earlier studied Himalayan events as well as CBb events in the rest of country. Figure 4 shows spatial distribution of highest ever recorded rainfall (cm) in 1 hr. Deshpande *et al.* (2012) studied 1, 3, 6 and 12 hr maximum ever recorded rainfall using 72 stations data for the period 1969–2005. Our results are in good agreement with their findings of heavy rainfall regions except for few pockets of heavy rainfall in past 2005 period. All India summer monsoon rainfall (AISMR) is 84 cm (Parthasarathy *et al.,* 1993). Rainfalls (~50 cm) over east peninsular India and northwest India are lower compared to AISMR. It is seen that rainfalls of 6–8 cm (1/10 of seasonal rainfall) have been recorded in 1 hr over these areas. For most parts of remaining India, highest ever recorded rainfalls in 1 hr range between 8 and 10 cm. West coast, Saurashtra subdivision and southern rim of north Himalayan region recorded rainfalls >10 cm in 1 hr. In some of these areas, the rainfalls are also seen to reach 12–16 cm/hr. These are the locations of CBb events. For more clarity, locations of only CBb events are shown in Figure 5. Table 2 gives the locations, mean sea level (msl) heights (or altitude) of the stations, date and hour of occurrence of the event, rainfalls in the CBb events along with the previous and following hour rainfall and duration (in hours) of rain spell in which CBb event occurred. There are total 28 CBb events. The msl heights of these stations are not very high except Dharamsala. The highest rainfall recorded in the CBb event was 191.20 mm on July 26, 1983 at Dharmshala as seen from the available data. There are stations where CBb events occurred multiple times. These are Dharmshala (Das, 2015), Bahraich (Das, 2015), Okha (Dash *et al.,* 2009), Veraval (Das, 2015) and Mumbai (Dash *et al.,* 2009). Mumbai has two IMD rainfall stations, viz. Colaba and Santacruz. The hourly rainfall data from Colaba has been available for the long period, hence has been used in this study Santacruz, a station in Mumbai, recorded 944 mm of rainfall on July 26, 2005. The rainfall more than 100 mm/hr occurred for first 3 hr (Vaidya and Kulkarni, 2007). So this rainfall event is composed of series of CBb events. On September 20, 2017, Santacruz received 304 mm, while Colaba recorded 210 mm rainfall. Mumbai's average rainfall for September is 312.3 mm. Rainfall of nearly month's total occurred in 1 day. The heavy rainfall event of September

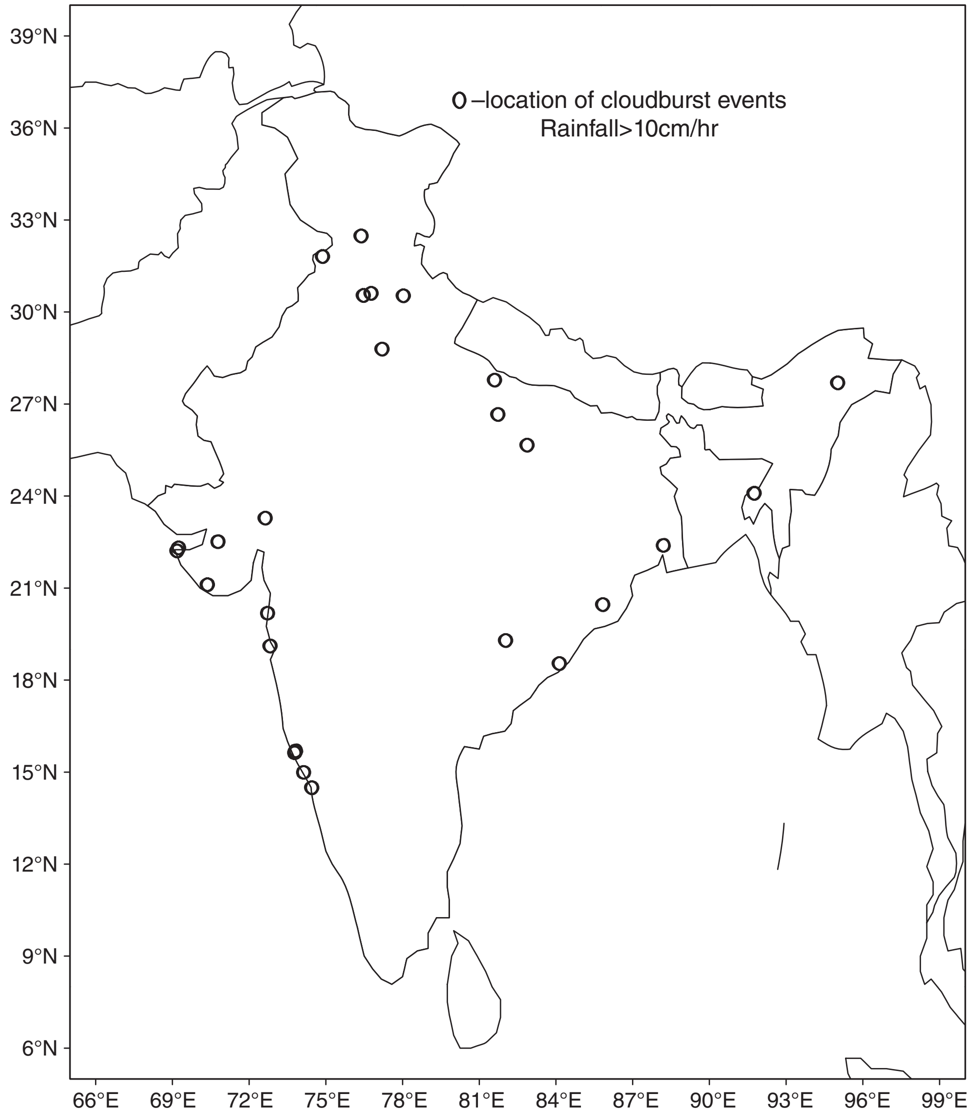

FIGURE 5 Location of cloud burst events (CBb)

20, 2017 at Santacruz was the combination of CBb and MCB events.

It is interesting to see from Table 2 and Figure 5 that most of the stations are located along west coast or southern rim of Himalaya. Khaladkar *et al*. (2009) reported record rainfall of 42 cm/hr at Cherrapunji on June 16, 1995. The highest monsoon rainfall stations on the west coast of India, viz. Mahabaleshwar, Agumbe, Amboli, Bhira do not appear in the list.

The orographic forcing is absent over these regions to trigger the CBb events. Hence, it is speculated that other mechanisms (synoptic-scale convergence and solar radiation) may be operating cohesively to form these events. The CBb events over west coast and Saurashtra region may be associated with mid-tropospheric cyclone (MTC) over Saurashtra subdivision, off shore west coast trough, and LPS over Madhya Pradesh. The CBb events over Uttar Pradesh may be associated with deep convective clouds in the monsoon trough region. Joseph *et al*. (2015) studied CB event which occurred in the state of Uttarakhand during June 15–17, 2013. They showed that the interaction between a monsoonal LPS and mid-latitude systems helped the generation of the heavy rainfall event aided by orographic uplift. The CBb events over western Punjab may be associated with interaction of mid-latitude westerlies and southerly moist monsoon winds. Medina *et al*. (2010) discussed the mechanism of intense convection over western Himalayan region. The moist airflow from Arabian Sea is energized by sensible heat flux over the Thar desert in western part of the country. Dry air flow from Afghan region, which is a part of mid-latitude westerlies, caps the moist low-level flow coming from Arabian Sea and Bay of Bengal and develops the convective instability. The convection is triggered by orographic lifting over the Himalayan foothills generating deep convection for CB events. Such orographic forcing is absent over the region of central India to trigger the CBb events.

The flash floods in the Himalayan CBa events result from the sudden downpour of the cloud water. Suddenness in time is the characteristic of the CBa event (Dimri *et al.*, 2017). We have examined this feature for all the 28 CBb

TABLE 2 CB Locations, altitude (m), occurrence time, rainfall (mm) corresponding to the CB event with the previous and following hour and duration of rainspell (in hours) containing CB event

CB event	WMO code	Stn name	Altitude (m)	Year	Month	Date	Hour	Rainfall	Previous hour	Following hour	Duration
1	42062	Dharamsala	1,547	1983	7	26	11	191.2	11.8	130.6	4
2	42062	Dharamsala	1,547	1983	7	26	12	130.6	191.2	0	4
3	42101	Patiala	351	1988	7	3	24	110	80.9	0	2
4	42103	Ambala	264	2002	9	12	20	100	6.7	1.3	9
5	42111	Dehradun	435	1970	6	14	11	101.1	45	1.2	4
6	42182	N.Delhi	216	1995	8	20	14	111.7	24	1.4	3
7	42273	Bahraich	126	1984	9	6	24	103	90	27	2
8	42273	Bahraich	126	1986	6	25	6	102.5	34.5	47.5	7
9	42475	Allahabad	98	1977	7	13	15	110	40	60	4
10	42479	Varanasi	81	1997	9	11	10	100	60	30	5
11	42647	Ahmedabad	53	2005	6	26	12	100	0	22.6	3
12	42724	Agartala	13	1969	8	18	8	103.7	33.8	29.7	17
13	42730	Okha	5	1973	7	10	4	134.8	9	67.1	8
14	42730	Okha	5	1998	7	1	23	113.4	8.5	22	7
15	42730	Okha	5	2007	8	5	13	103.5	56.5	90.2	16
16	42737	Rajkot	128	1978	6	15	18	115.6	30	6	5
17	42909	Veraval	0	1984	7	19	6	134.4	4.5	23	8
18	42909	Veraval	0	2009	7	15	17	100	50	40	17
19	42971	Bhubaneshwar	45	1971	6	22	3	120	70	50	11
20	43041	Jagdalpur	552	1974	6	16	24	111	29	60	13
21	43057	Mumbai	4	1975	7	31	3	110	25.5	95.3	7
22	43057	Mumbai	4	1990	6	16	1	113	60	73	7
23	43057	Mumbai	4	1998	6	27	13	100	20	10	11
24	43192	Panjim	7	1998	7	23	1919	129.5	5.2	24	11
25	43196	Mormugao	10	1998	7	24	22	125.5	28.9	9.5	9
26	43225	Karwar	6	1998	6	19	1	105	12.5	23.5	10
27	43311	Aminidivi	2	2004	5	5	11	100	70	50	20
28	43333	PortBlair	16	1977	7	21	11	122	83.2	44	4

events. The rainfalls in 1 hr previous, 1 hr after the CBb event and duration of rain spell in the CBb event have been studied. Table 2 gives the rainfall in these hours along with the duration of the rain spells in the CBb events. It is seen that in 22 cases, rainfalls more than 10 mm occurred in the previous 1 hr. The duration of the rain spell ranged between 2 and 20 hr. These indicate that CBb events are not sporadic like CBa events. These are embedded in the mesoscale cloud systems. The rainfall in the previous hours, higher duration of rain spells and the rainfall from CBb together cause high flood potential in the areas of CBb events. Numerical modelling studies are required to decipher the conditions in which the some selected cloud cells intensify to CBb stage to produce heavy downpour.

3.1.2 | Mini-cloud burst

Figure 6 shows the spatial distribution of highest recorded rainfall in MCB events. The highest recorded rainfall varies from 7 cm to >22 cm in 2 hr. Over most parts of India the highest recorded rainfall in 2 hr ranges between 10 and 15 cm which is quite large and having potential of causing damages similar to CBa event. The locations of maximum recorded rainfall >15 cm in 2 hr are coinciding with CBb events. This indicates that the mechanism responsible for heavy rainfall event persists for more than an hour, resulting in to high potential of flash floods and damage to properties. This finding may give impetus for more detailed studies of such events.

3.2 | Temporal distribution of MCB

3.2.1 | Mean MCB per season

Figure 7a shows the mean MCB events per monsoon season over the Indian region. The mean is based on the available data period for each station. It is clearly seen that MCB events are very common at the foothills of Himalaya and along the west coast with frequency more than three events per season. Such events occur in Indo-Gangetic plains and Saurashtra subdivision with frequency more than two per season.

The lowest number (on an average at most one per year) of MCB events are seen over the Rajasthan and leeside of the Western Ghats (WG). The leeside of the WG is the rain-shadow region. The region is dominated by the anticyclonic vorticity at lower troposphere due to dynamic

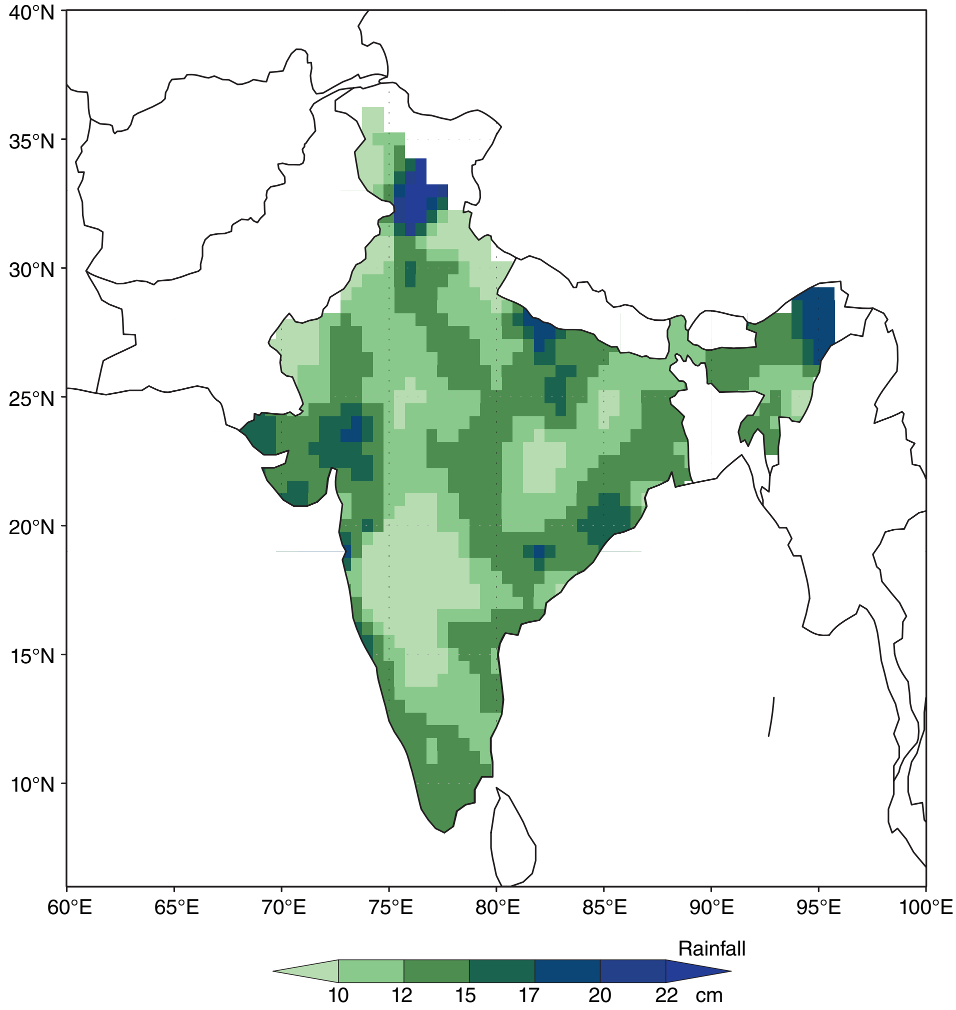

FIGURE 6 Extreme rainfall in MCB events (cm) [Colour figure can be viewed at wileyonlinelibrary.com]

effect of the WG (Narkhedkar *et al.,* 2015). This anticyclonic vorticity inhibits the growth of deep convective clouds essential for occurrence of MCB. Such deep convection essential for MCB formation is also absent during monsoon season over Rajasthan in northwest India. This may be the reason of low MCB events over these regions.

The orographic lifting in addition to synoptic scale upwards motion and advection of moisture from Bay of Bengal and Arabian Sea are favourable conditions for the formation of deep convective clouds over the foot hills of Himalayas, WG and northeast India. The high MCB events over these areas may be attributed to orographic effect. Deep convection formed during the MTC moving over Saurashtra region from the Arabian Sea, in the monsoon season (Miller and Keshavamurthy, 1967) may be responsible for MCB over Saurashtra region.

Frequency of two to five MCB events per season is observed over central India and monsoon trough region. The LPS are formed over Bay of Bengal and Odisha coast in the monsoon season. They travel in the northwest direction over the central India. The deep convection associated with the LPS produce MCB over central India. The monsoon trough is the seat of deep convection. This convection produces favourable conditions for MCB over the trough region. Table 3 gives the list of stations where MCB events occur frequently (>1 event/year). Besides these stations, many stations record MCB during monsoon season though not every year. On an average around 200 MCB events occur every year in India. It has been observed that maximum number (around 265) of MCB occurred in the year 1988 and 2007 which were the excess monsoon rainfall years for India as a whole. Correlation between number of MCB events and corresponding seasonal rainfall of that region, indicate that seasonal rainfall are significantly correlated (at 5% level) with MCB events in the region, with p value quite smaller than 0.05. Except for northeast India, it has been observed that number of MCB events are quite large in excess or normal monsoon year.

3.2.2 | Variability in MCB

Figure 7b shows coefficient of variation (CV in %) (defined as standard deviation/mean*100) over India. It is seen that CV values are less than 100 in the region of high MCB regions. The maximum CV of 175% is seen over NW India and leeside of WG. These are areas of low MCB regions. Over central India CV ranges between 100 and 125%.

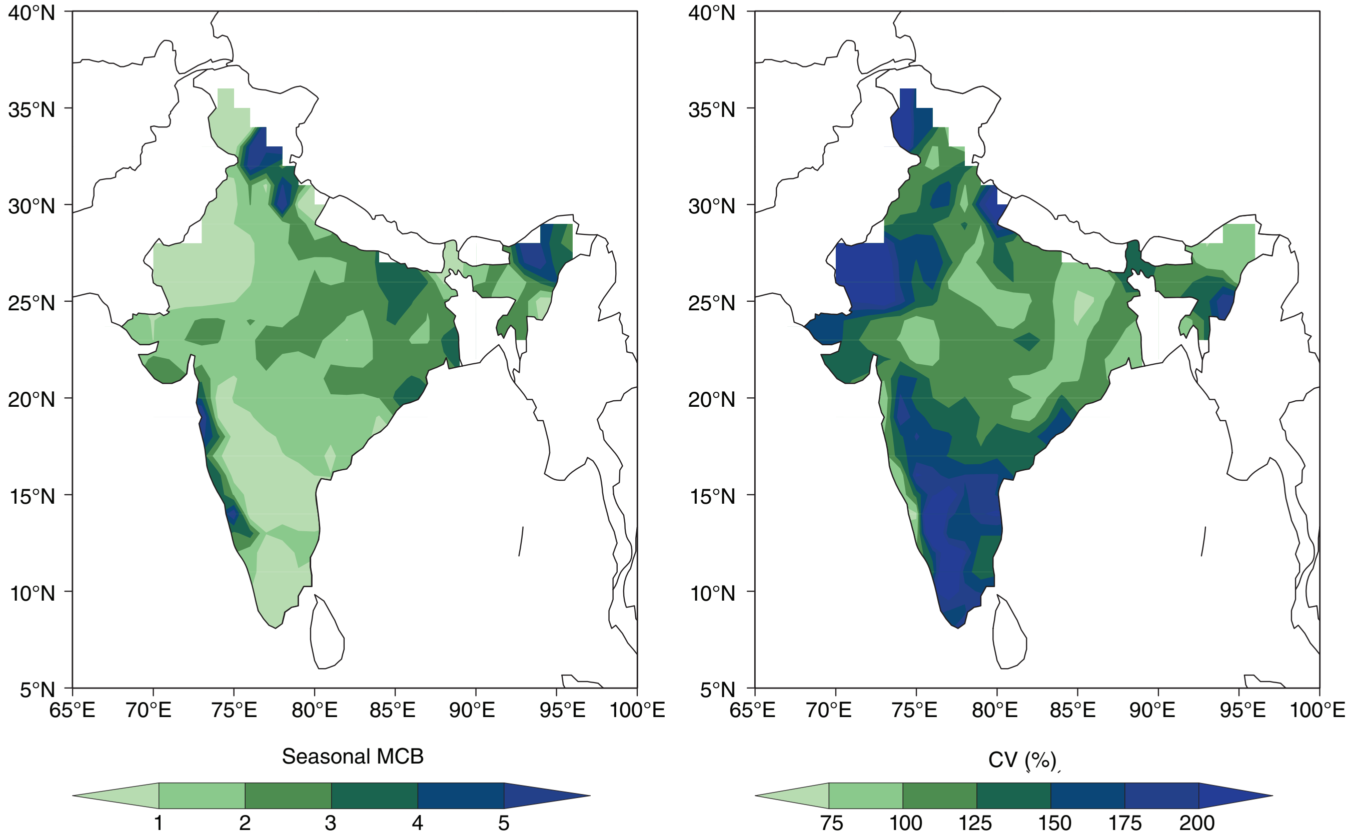

FIGURE 7 (a) Mean MCB events (b) coefficient of variation (%) of MCB [Colour figure can be viewed at wileyonlinelibrary.com]

3.2.3 | Monthly distribution of MCB

As the frequency of MCB events per monsoon months is low, the MCB events are computed for 10 year period. Figure 8 gives the spatial patterns of MCB events in each of the monsoon months. It is seen from the Figure 8 that in the month of June, west coast stations such as Mumbai, Ratnagiri, Panjim, Marmgao, Karwar, Honavar and Agumbe record MCB events with average frequency two. Stations from northeast India such as Agartala and North Lakhimpur also record these events in the month of June which is the onset month of the monsoon season in these areas.

Once the monsoon is established in the northern parts of the country, station in the western Himalaya such as Dharmsala, Ambala, Dehradun, and stations like Mahabaleshwar, Agumbe and Mumbai in south record MCB events in the months of July and August. In the month of September, the deep convective activity is rarely seen in the country as a result MCB events are very rare without any systematic pattern. They are seen along the foothills and east coast region. It is quite interesting to note that though located in the Himalayas, stations like Shrinagar, Gulmarg, Imphal and station Kodaikanal located in southern part of the WG receive MCB events very rarely during the monsoon season. Simultaneous occurrence of MCB has been observed in some cases under the influence of certain synoptic situation. Two such examples are discussed here. One corresponds to onset phase of monsoon (June 14, 1996) and another with active phase of monsoon in northern India (July 18, 1975). As June 14, 1996 was onset phase of monsoon, most of the places are in the peninsular India. In all, 24 MCB events occurred on that day out of which maximum events are recorded at Agumbe—a heavy rainfall station in WG region. Another episode of the heavy rainfall was shown during the active phase of monsoon. In all 10 MCB events occurred on July 18, 1975 out of which maximum occurred at Ajmer in Rajasthan state. Note that though MCB occurred at different locations on the same day, they occurred at different times during that day. Figure 9 shows the spatial pattern of the rainfall intensity (mm/event) in MCB events in the four monsoon months. It is seen that in June, intense MCB events occur at Gujarath coast and east coast of Odisha, Some parts

TABLE 3 List of stations with frequent occurrence of MCB events

Average frequency per year	Name of the station
1–2	Patiala, N. Delhi, Shahajahanpur, Gwalior, Lucknow, Sultanpur, Guwahati, Allahabad, Varanasi, Ahmedabad, Bhopal, Jabalpur, Okha, Rajkot, Indore, Porbandar, Raipur, Jharsuguda, Akola, Kanker, Jagadalpur, Ramgundam, Mangalore, Kozhikode
3–5	Ambala, Moradabad, Bareilly, Bahraich, Dibrugarh, Gorakhpur, Patna, Gaya, Silchar, agartala, Kolkata, Porbandar, Digha, Veraval, Bhubaneshwar, Dahanu, Puri, Ratnagiri, Mahabaleshwar, Panjim, Marmgao, Karwar, Honavar, Porbandar
>5	Dharamsala, Dehradun, North Lakhimpur, Mumbai, Agumbe

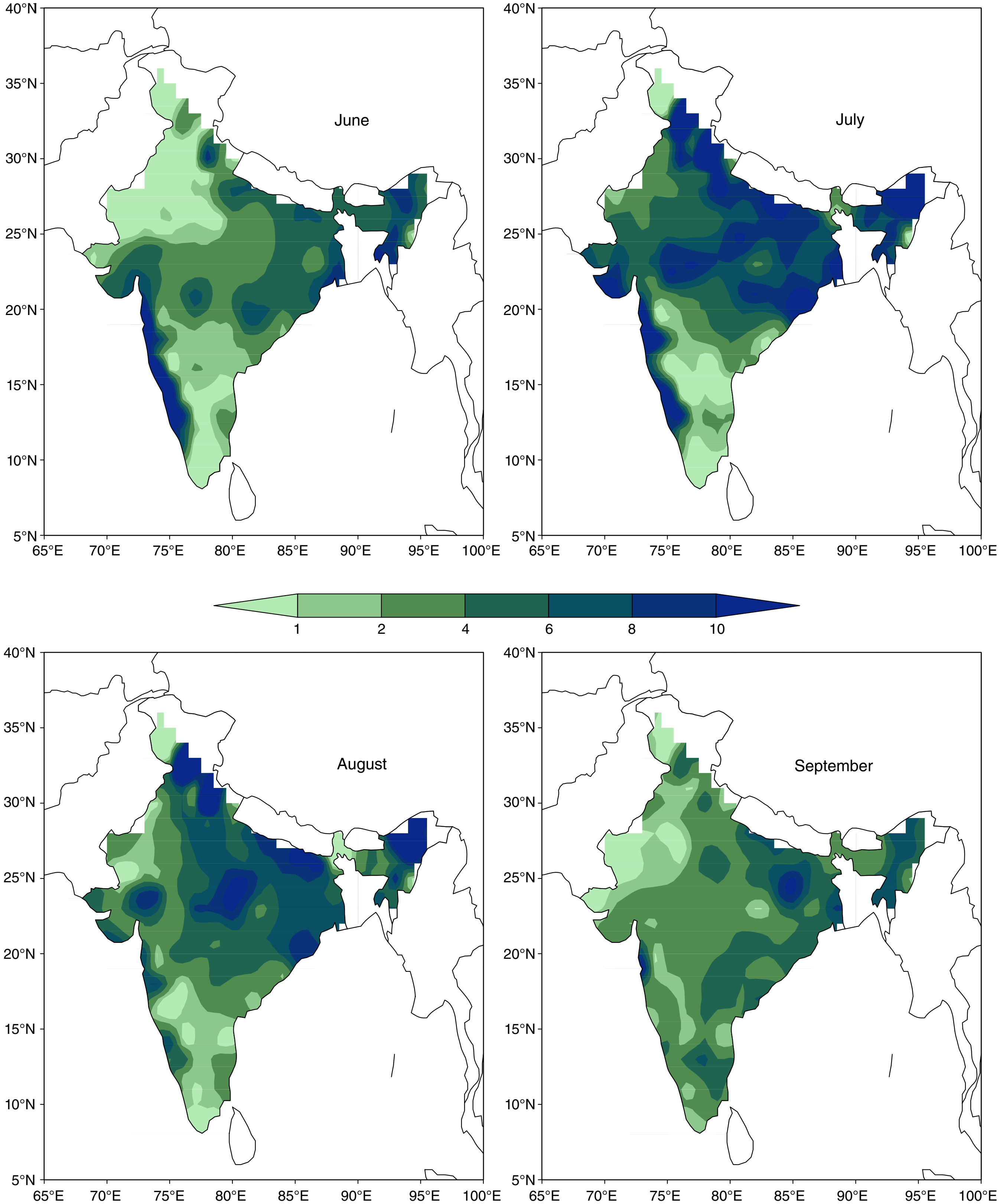

FIGURE 8 MCB distribution (per 10 years) during monsoon months [Colour figure can be viewed at wileyonlinelibrary.com]

of Uttar Pradesh and northeast India, with average intensity of rainfall exceeding 7.0 cm per event. This is due to the passage of monsoon current from the Arabian Sea and Bay of Bengal, respectively, during the onset phase of monsoon season. For rest of the MCB region, it ranges between 5 and 7 cm. Most part of the north India receives rainfall more than 6 cm during MCB events in July–August months. Though MCB events reduce in the month of September, they are very intense over Indo-Gangetic plains with intensity exceeding 7 cm per event.

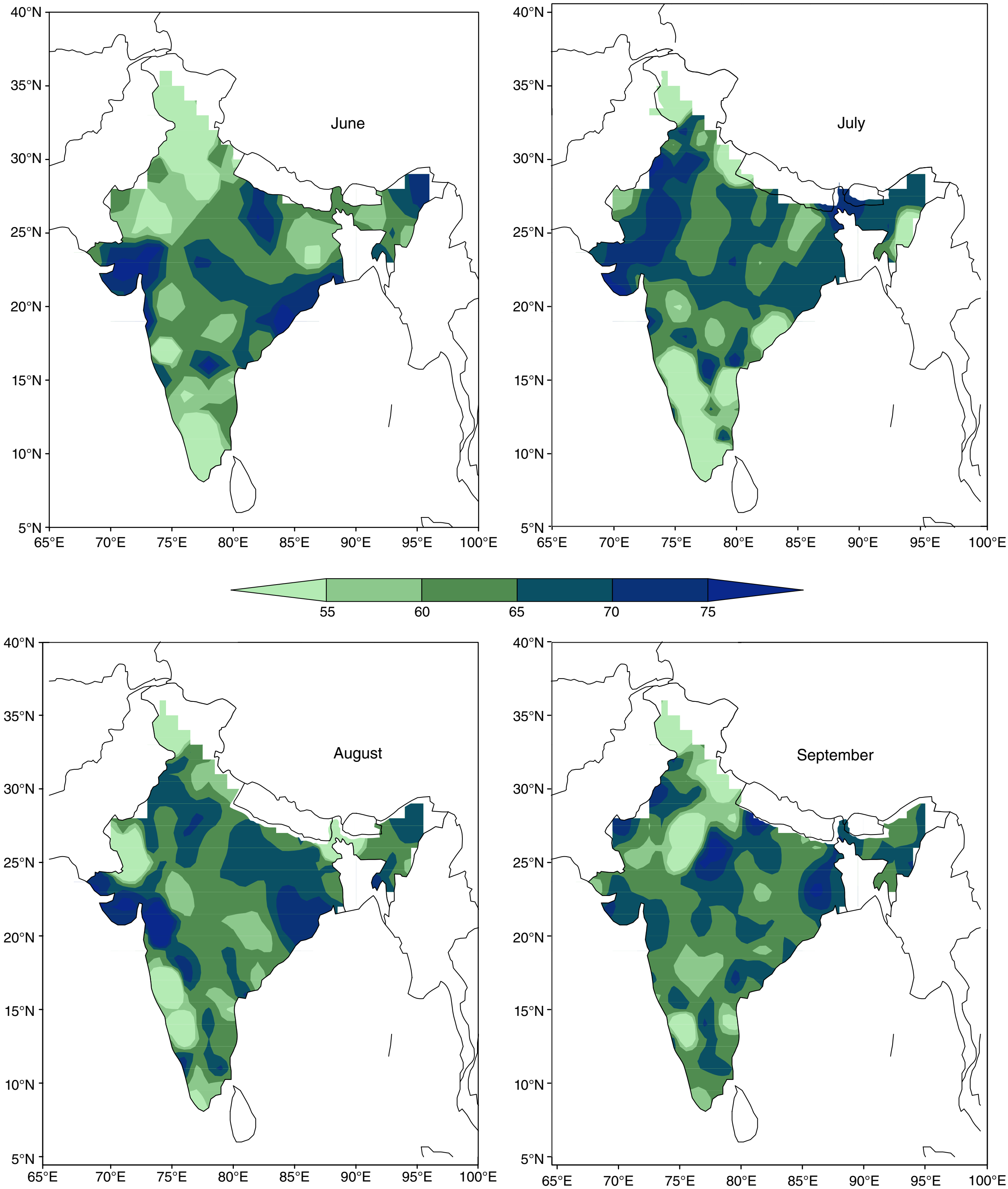

FIGURE 9 Monthly distribution of rainfall Intensity (mm/event) of MCB events [Colour figure can be viewed at wileyonlinelibrary.com]

3.2.4 | Diurnal variation

To study the diurnal variation of MCB events during the monsoon season, the day is divided into four quarters of 6 hr each. These are 0000–0600, 0600–1200, 1200–1800 and 1800–2400 LST (UTC+5.30), respectively. Figure 10 displays the spatial pattern of frequency of MCB events in four time periods during a day for the monsoon season.

It is seen from the figure that in the morning hours (0–6 and 6–12 LST), frequent occurrences of MCB events are seen along the foothills of Himalaya and west coast region of India where orography plays an important role in the rainfall process. While central part of India is seen to record MCB events in the afternoon hours (12–18 LST). In the region of south peninsula, MCB events occur during the night hours (18–24 LST).

3.3 | Temporal changes in the MCB events

It has been shown by Das (2015) that in recent years the frequency of CBa events in Garhwal-Kumaon Himalayan region has been increasing continuously. One important

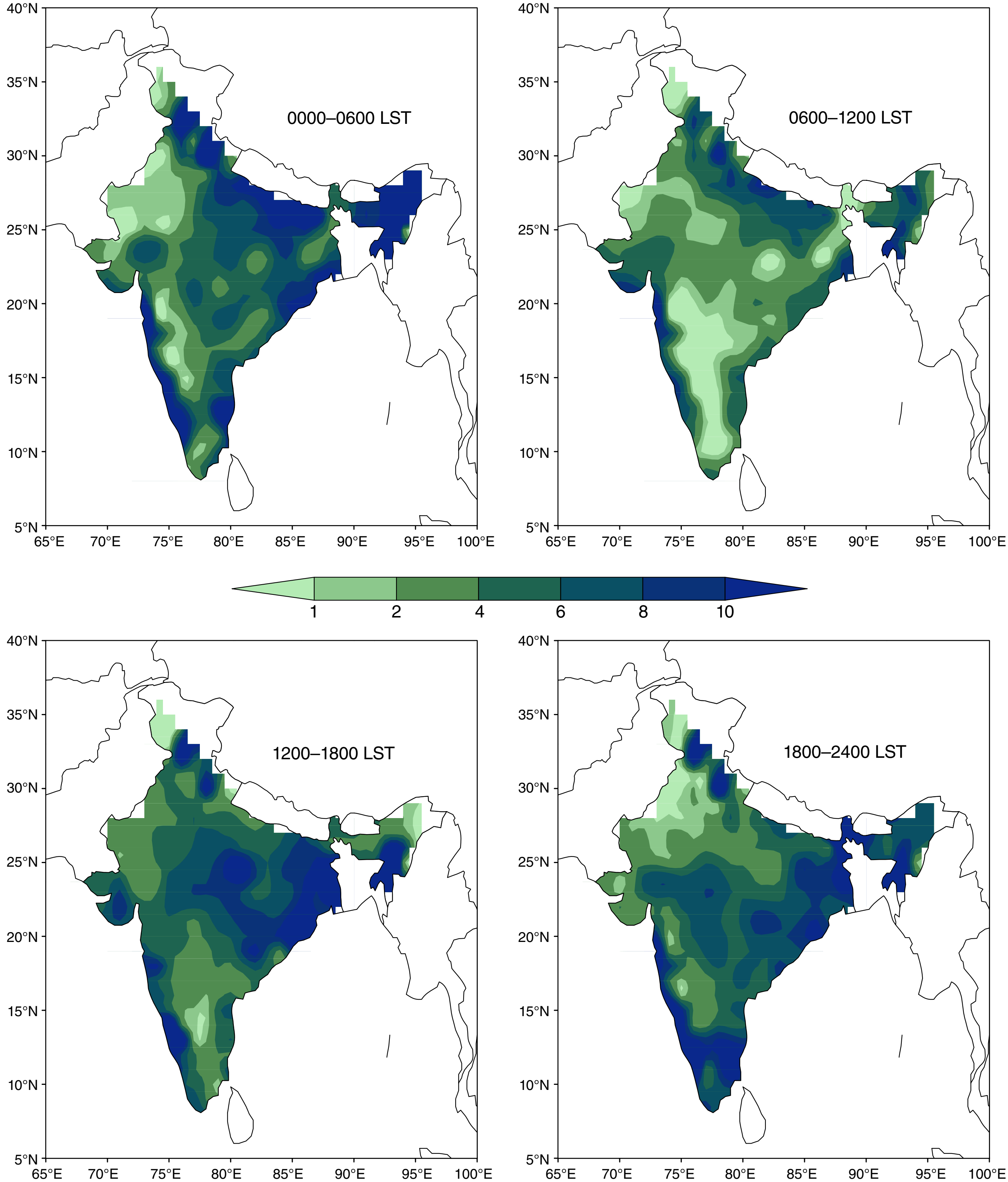

FIGURE 10 MCB distribution as per their time of occurrence during a monsoon day [Colour figure can be viewed at wileyonlinelibrary.com]

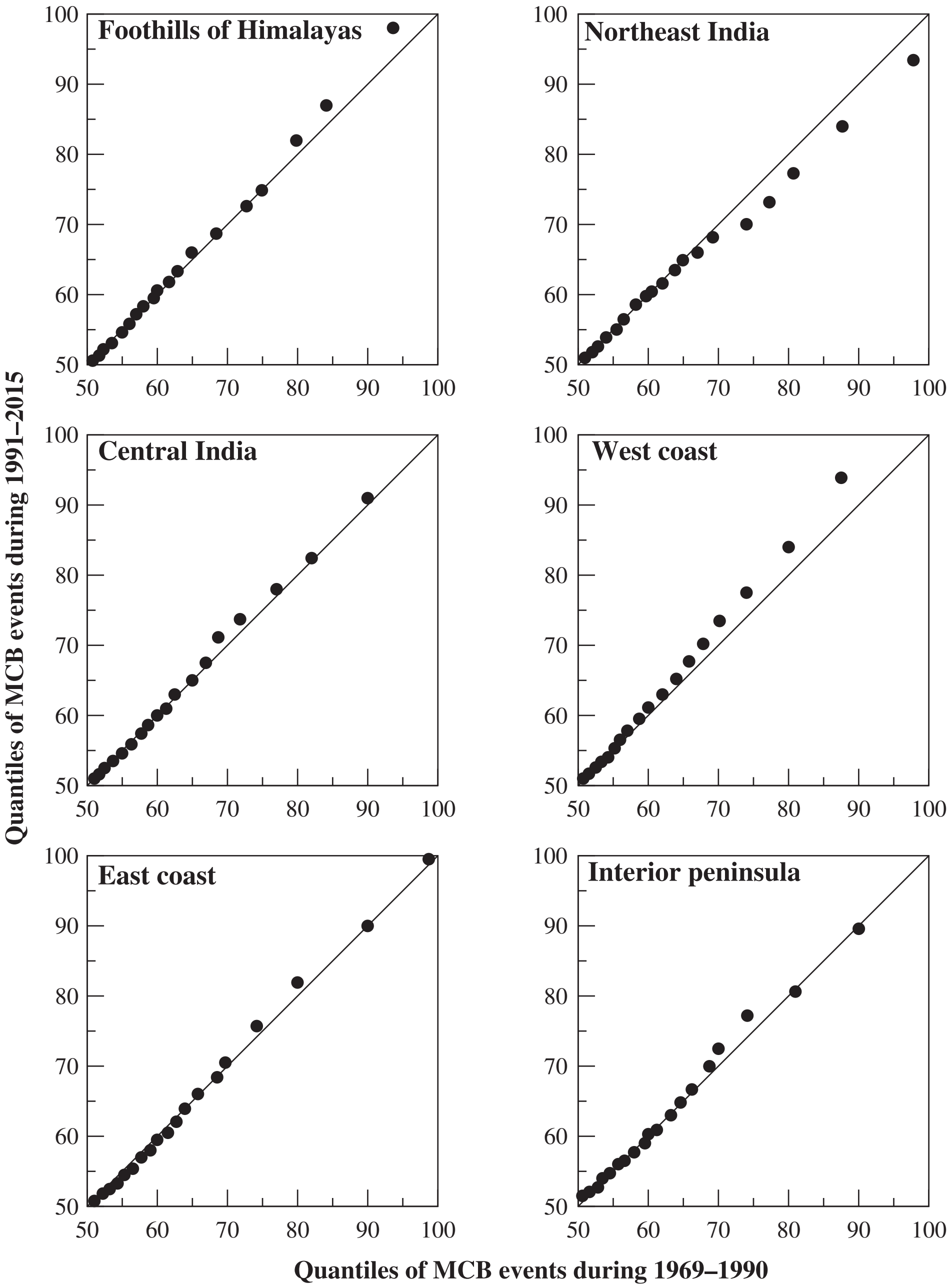

FIGURE 11 Quantile–quantile plot of MCB events prior 1990 versus post 1991 period in six regional zones

cause pointed out by the author is the faster evaporation rate from high-altitude glacial lakes due to global warming. The study by Goswami *et al*. (2006) showed increase in extreme rainfall events over central India. This increase in extreme events has been hypothesized to intensification hydrological cycle. Dash *et al*. (2009) analysed the gridded daily rainfall data sets during 1951–2004 and inferred that the frequencies of moderate and low rain days over entire country have significantly decreased in the last half century. They further reported that long spells are decreasing while short and dry spells indicate an increasing tendency at 5% level of significance. Deshpande *et al*. (2012) used station hourly rainfall data and showed significant increasing trend (at 5% level) in the extreme rainfall events of short duration (3–12 hr) at many stations in central India and peninsular India. These facts prompted us to examine the impact of global warming on number of MCB events over India. This is achieved by applying quantile plot technique (Q–Q plots) to the number of MCB events in past period (1969–1990) and post 1991 period, for six regions in India. Trend analysis has also been carried out at some selected station showing frequent occurrences of MCB events.

3.3.1 | Quantile plots for MCB events across six homogeneous regions

Q–Q (quantile–quantile) plot is a graphical comparison of two probability distributions by plotting their same quantiles against each other (Wilk and Gnanadesikan, 1968). In the present study, Q–Q plot technique is used to examine the temporal changes in the MCB events across six homogeneous regions, namely, foothills of Himalaya, northeast India (east of 87°E), central India (20°–27°N and west of

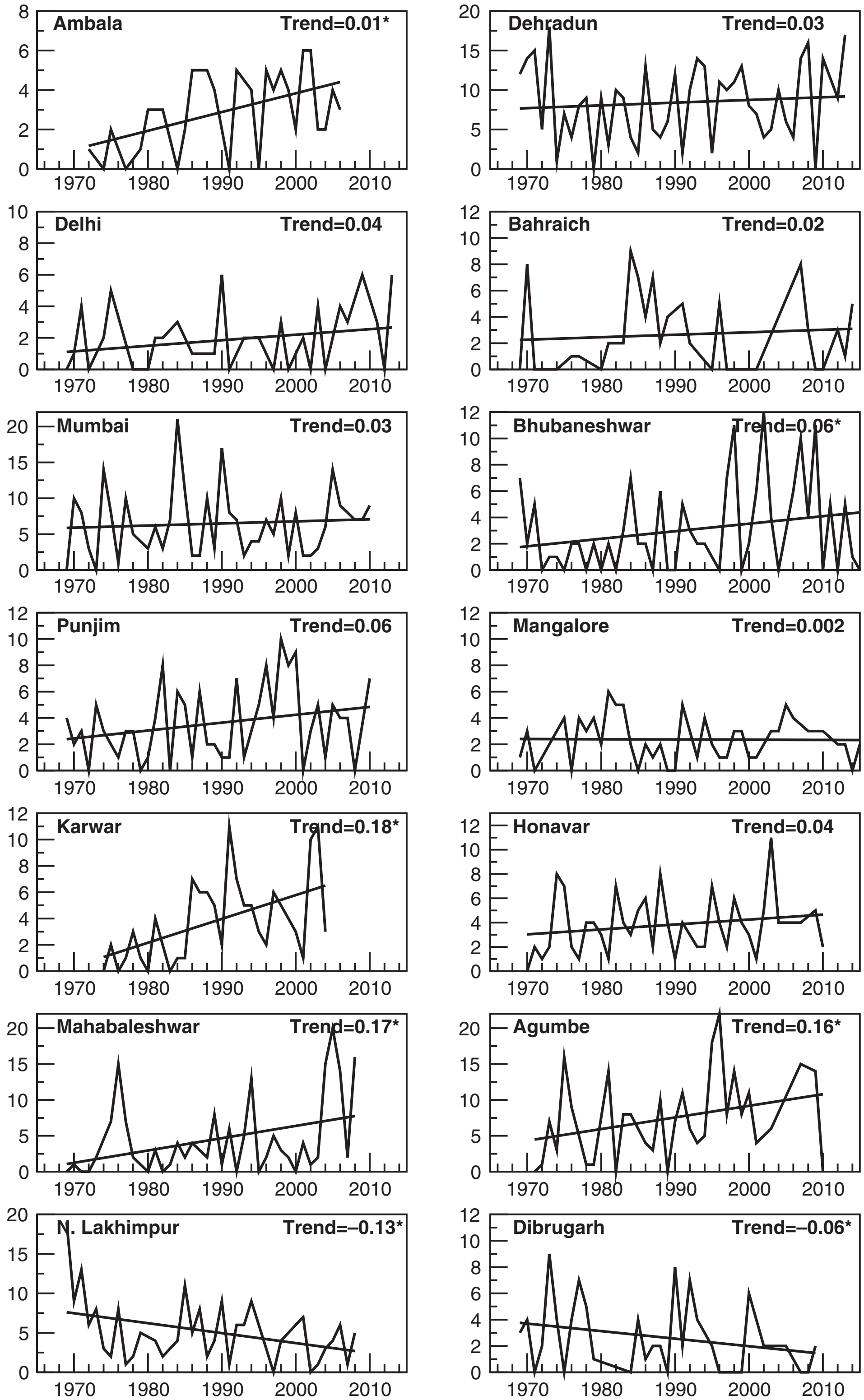

FIGURE 12 Time series plots and fitted Linear regression of MCB events at some selected stations during 1969–2015 (significant trends are marked with *)

87°E), WG and west coast, east coast and interior peninsula lying south of 20°N. These regions are defined on the similar basis to that of Kothawale and Rajeevan (2017) and Dash *et al*. (2009). Data sets have been divided into two parts, prior 1990 and post 1991. For each of these six regions, two groups of MCB events are formed corresponding to two time periods, considering the stations lying within each region. Then within the group, MCB events are arranged in the ascending order. Different quantiles (5th, 10th,…. 95th percentiles) are evaluated from these two groups and are plotted against each other. The procedure is repeated for all the six regions. Figure 11 shows the quantile plots for six regions. It is seen from the figure that two groups do not appear to have same distribution for all the six regions. Lower quantile values lie on the line $x = y$ indicating no temporal changes for smaller values but higher quantile values deviate more in two groups. In case of foothills of Himalayas and west coast and WG, higher quantile values are larger in post-1991 years indicating intensity of MCB events tend to be more in recent years, while for northeast India higher quantile values in recent years (post-1991) lie to the lower side to that of prior 1990 period, indicating decrease in the intensities of MCB events. This region also shows a significant decreasing trend in the summer monsoon rainfall during 1901–2014. (Preethi *et al.,* 2017).

3.3.2 | Trend analysis of frequency of seasonal MCBs at selected stations

Temporal changes in the MCB events are examined for six homogeneous regions of India using QQ plots as discussed in the previous section. However, to quantify these temporal changes, trends in the seasonal number of MCBs at some selected stations are tested at 5% level of significance. These stations are selected on the basis of the data availability and frequent occurrences of MCB events at these stations. Figure 12 shows the time series plots of the seasonal MCB events at selected stations along with the fitted linear trends. Significant trend has been marked with (*). Figure indicates that at many places across the country these events are increasing significantly such as some stations in the northern India, viz. Ambala and Dehradun, stations in the WG such as Agumbe and Mahabaleshwar and west coastal stations such as Karwar and Panjim However stations Dibrugarh and North Lakhimpur in northeast India show significant decrease in the frequency of these events.

4 | SUMMARY AND CONCLUSIONS

A new and broad definition of CB event has been proposed which covers CBa events triggered by orography in Himalayan region and CBb events in rest of India in which rainfall in 1 hr exceeds 10 cm. A new high rainfall event called MCB has been coined. The analysis of CBb and MCB events has been carried out using hourly rainfall data of 126 wide spread stations during the period 1969–2015 for the monsoon season to bring out their statistical characteristics. The study brought out that there are around 26 CBb events over the low orography region and plains of India. The orographic forcing is absent over these regions to trigger the CBb events. Hence it is speculated that other mechanisms (synoptic-scale convergence and solar radiation) may be operating cohesively to form these events. The spatio-temporal variability of MCB events has been studied. The study showed that these generally occur in the month of June at many stations in the WG. In the months of July, August, at stations located at foothills of Himalaya experience these events. In September these events hardly occur in India. The MCB events generally occur in the early morning hours at foot hills of Himalaya and along the west coast. In the interior of the land region MCB events are observed in the afternoon hours while in the interior peninsular India these occur at night. Temporal changes in the number of MCB are noticed all over the country. The study indicated significant increase in MCB events at many places in India, except northeast India. The statistics of CBb and MCB events provided in the study may find useful for the diagnostic and numerical modelling studies for understanding the mechanism underlying these events.

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