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Assessment and review of hydrometeorological aspects for cloudburst and flash flood events in the third pole region (Indian Himalaya)

Amit Kumar[a,*], Anil K. Gupta[b], Rakesh Bhambri[a], Akshaya Verma[a], Sameer K. Tiwari[c], A.K.L. Asthana[c]

[a] Centre for Glaciology, Wadia Institute of Himalayan Geology, Dehra Dun, 33, GMS Road, Dehra Dun, 248001, Uttarakhand, India
[b] Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur, 721302, India
[c] Wadia Institute of Himalayan Geology, Dehra Dun, 3, GMS Road, Dehra Dun, 248001, Uttarakhand, India

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ABSTRACT

Impacts of global climate change can be seen worldwide, both on developing and developed economies. In recent years, numerous researches have been carried out by the Government and Non-Government agencies in understanding, assessing, predicting, and responding to expected processes of global climate change and recommend policies for mitigation. Extreme weather events like increased precipitation, cloudbursts, flashfloods, and avalanches in the mountainous region threaten human lives, and state and national economies. In the Indian Himalayan Region (IHR), well distributed hydrometeorological records (contemporary and historical) that facilitate the understanding of processes driving extreme weather events are scarce or rarely available. However, the capacity to observe, measure and quantify precipitation on regional scales has increased tremendously over the last three decades. Topography of the IHR provides favorable conditions for the cloudburst phenomenon which lead to frequent flashfloods and landslides; killing hundreds of people every year. Understanding the exact mechanism of the driving processes of cloudbursts such as orographic lifting, precipitation distribution, precipitation thresholds and its source or origin are still uncertain. Keeping in view that cloudbursts have been increasing in both their frequency and intensity, they are likely to intensify in the near future. Present study analyzes and critically summarizes facts and impacts of cloudburst events through compilation of hydrometeorological records and analysis of available data in the IHR. Results indicate that natural climate variability has played a much greater role in driving these extreme events than earlier thought. A general consensus is observed about the role of climate change, large atmospheric circulations, teleconnections and landuse–landcover changes in driving these events. Therefore, in light of such challenges and potential research gaps, this paper aims at producing actionable knowledge in the IHR for climate modelers and policy planners to better serve the nation's needs.

1. Introduction

After the polar regions of Arctic, Antarctic, and Greenland, the Himalaya holds the largest accumulation of snow and ice in the world. The Himalaya is warming faster than the rest of the world, and it is the source of major rivers systems that support more than one billion people (IPCC, 2013). It has been observed that global air specific humidity has increased and amount of water vapor in the atmosphere has increased due to human-induced warming (Easterling et al., 2000; Trenberth et al., 2003). More availability of water vapor in a warmer atmosphere consequently increases the potential of intense precipitation (Dai, 2006; Willett et al., 2008; Simmons et al., 2010). Therefore, unambiguously, frequency and intensity of extreme precipitation events have increased because of the global climate change across the world (Burt, 2005; Clark, 2005; Goswami et al., 2006; Joshi and Rajeevan, 2006; Solomon et al., 2007; Ghosh et al., 2012; IPCC, 2013; Devrani et al., 2015; Kasprzak and Migo, 2015). The heavy rainfall events have become heavier and more frequent, and the highest amount of rain falling on the rainy days has also increased worldwide in recent years (Houghton et al., 1996; Wang et al., 2014; Mayowa et al., 2015). Disasters triggered by excessive moisture include cloudbursts, flashfloods, landslides etc caused by unusual rainfall events that result in loss of life and damage to millions of dollars of property annually in the IHR as well as other parts of the Indian landmass (Bohra et al., 2006; Allen

* Corresponding author.
E-mail addresses: amithydrocoin@gmail.com, amitwalia@wihg.res.in (A. Kumar).

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et al., 2016; Balakrishnan, 2015; Ruiz-Villanueva et al., 2017).

In the Himalayan region, shifting patterns of rainfall are a consequence of climate change and the mechanism driving these changes is not well understood. Intense precipitation rates typically involve some connection to monsoon air masses that are laden with heavy moisture and heat because of tropical origin (Kelsch et al., 2001; Gruntfest and Handmer, 2001). Woolley et al. (1946), designated the term “cloudburst” as torrential downpour of rain at high intensity associated with thunder, bursting and discharge of the whole cloud at once over a relatively small area. The authors also emphasized that such events are common in mountainous regions, leading to torrential and destructive floods in small basins.

In the Himalaya, the expression of cloudburst is defined as localized weather phenomenon representing rich concentration of rainfall over a small area lasting for few hours, and leading to flash floods/landslides in the region. In other words, cloudbursts are associated with intensive heating of air masses, their rapid rising, and thundercloud formation (Kumar et al., 2012; Kumar et al., 2016a,b). The major difference between cloudburst and heavy rains is in the amount of water and its duration of pour down on the Earth (i.e. intensity of rainfall). The rainfall amount precipitated in a day ranging between 124.5 and 244.4 mm is categorized as “very heavy rainfall” event and greater than 244.5 mm is categorized as an “extremely heavy rainfall” event, while rainfall over 100 mm per hour is referred as a cloudburst event (India Meteorological Department). A cloudburst is quite unexpected and very abrupt in nature. Apart from the monsoon season (July–September), cloudburst occurrences are also observed during May and June linked with severe convective weather activities as well as links to the mid-latitude/polar jets (Table 3). No satisfactory technique is available to anticipate occurrence of cloudburst because they occur swiftly in a small area. A cloudburst can occur anytime and at any place affected by the convective weather systems, Himalaya is a favored location for the genesis of such convective weather events.

Meteorologists explain cloudbursts as mesoscale thunderstorms or extreme precipitation amount, sometimes with hail and thunder capable of creating flash flood conditions. If the right combinations of atmospheric conditions like instability, moisture content and triggering mechanisms are available, cloudbursts can be triggered in a short span of time. To understand this, authors attempt to recognize the possible facts and impacts of extreme events and their associated hazards in the IHR. The extreme events observed in IHR have been studied in an outlook of their spatial and temporal distributions, trends and the governing mechanisms. In the present study hydrological and meteorological data collected from different locations in the Himalayan region have also been analyzed and discussed.

Review indicates that natural climate variability has played a much greater role in driving these extreme events than earlier thought. Also, the role of large atmospheric circulations as well as teleconnections like ENSO, NAO (El Nino Southern Oscillations, North Atlantic Oscillations), etc. on the variability of the Indian Summer Monsoon (ISM) is important and has only been reported by a few researchers and needs to be further investigated (Gupta et al., 2003; Sun and Wang, 2012; Liu and Yin, 2001; Afzal et al., 2013). The link between Eurasian snow cover and the southwest monsoon on a centennial scale has also been established by Anderson et al. (2002). Studies based on reanalysis data and prediction models shows that the upper level winds (e.g., Jet streams) have a considerable influence on the surface weather patterns including the ISM (Rao et al., 2004; Goswami, 2005; Watanabe and Yamazaki, 2012; Sreekala et al., 2014). The probability of occurrence of extreme rainfall events over Western Himalayan region has increased as a result of enhanced interactions between ISM and penetrating westerlies (Priya et al., 2016; Kripalani et al., 1997). Further, the rainfall over the northern hemisphere is influenced by the summer NAO (Folland et al., 2009; Linderholm et al., 2011). The teleconnection of NAO and SST (sea surface temperature) in North Atlantic have been linked to the ISM circulation as well (Liu and Yin, 2001; Srivastava et al., 2002, Li et al., 2008, Sun and Wang, 2012; Afzal et al., 2013; Krishnamurthy and Krishnamurthy, 2016). However, due to lack of comprehensive information about the atmospheric circulation, related processes and constraints in observational and modelling techniques, there is still a large uncertainty in the prediction of such extreme events (Xavier et al., 2018).

Therefore, in light of such challenges and potential research gaps, the authors aim at producing actionable knowledge in the IHR for weather modelling and policy planners to better serve to the needs of the nation. Although, numerous studies have simulated these events using variety of prediction models worldwide, the applications of Weather Research Forecasting (WRF) model and reanalysis data pertaining to the Himalayan region are discussed in detail. The awareness towards the climate extremes and their consequences has increased over the past decades because of the demand for scientific information from both the public and private spheres. The non–cyclic behavior of cloudburst events and the identification of available moisture for triggering cloudburst events are still unknown. In this study, the authors attempt to identify moisture source availability for cloudbursts, based on the Lagrangian framework in which the movement of air parcels through space and time are described by backward wind trajectories reaching any particular location (Gustafsson et al., 2010; Deshpande et al., 2015; Huang and Cui, 2015; Kumar et al., 2018).

2. Methodology

The present study involves extensive review of literature regarding the cloudbursts and their associated events in the IHR. However, previous studies provide limited information regarding the location, timing and economic losses, while little or no understanding about the hydrometeorological aspects is available. Therefore, tabulation and extraction of meteorological conditions which reflect the trends and spatial patterns of the events have been utilized (Table 1). The cloudburst incidence and intensity in different areas have been divided into different zones i.e. Uttarakhand and Himachal region, northwest Himalaya. The above information is essential for deriving appropriate understanding of the adverse impacts of cloudbursts. Further, the spatial information on the entire cloudburst events and other associated hazards were extracted from the digital elevation model (DEM). For this, Shuttle Radar Topography Mission (SRTM) elevation data at 30 m resolution was utilized to understand any topographic influence in the distribution of the compiled cloudburst events (Fig. 1). We produced topographic swath profiles across the Himalayan range in order to gain average, maximum and minimum altitude along a profile. The attributes of the events have been extracted from the longitudinal profiles.

To further strengthen the study with consequences to compile information about the cloudburst and associated events, we have analyzed meteorological records (Air temperature and Atmospheric pressure) collected by automatic weather stations (AWS), installed at different altitudes (Tela Camp, 2540 m a.s.l; Base Camp, 3763 m a.s.l; Advanced Base Camp, 4364 m a.s.l) and hydrological data in Dokriani Glacier catchment during the year 2013. Also, hydrometeorological records for Chorabari Glacier catchment during the year 2013 were also analyzed. The hydrometeorological data collected during the extremes gives insight to understand its variability and distribution in the higher altitudes. Therefore, daily rainfall data was collected manually using ordinary rain gauge (ORG) with daily resolution at 08.30 and 17.30 h (India Meteorological Department). The details of the accuracy and resolution of the sensors of the AWS can be accessed from Kumar et al. (2018) and Verma et al., 2018 for Chorabari and Dokriani glaciers, respectively. However, daily discharge of meltwater draining from glaciers was collected near the snout. Therefore, the calculations of surface velocity, mean velocity, and discharge were estimated by the well described area–velocity method developed for the Himalayan streams (Singh et al., 2011; Kumar et al., 2016a,b). After calculating melt discharge, an empirical relation between discharge and water level

Table 1
Recent landslide, cloudburst and associated flash flood events recorded in the Indian Himalayan Region (IHR) (modified after Kumar et al., 2016a,b).

Events	Date	Area	Period
Rainfall-induced landslide[a]	20 July 1970	Belakuchi (Birahi River), Uttarakhand	M
Rainfall-induced landslide[a]	August 1981	Mandakhal Pauri Garhwal, Uttarakhand	M
Cloudburst[w]	22-July 1983	Karmi Village, Almora, Uttarakhand	M
Cloudburst-flash flood[c]	29 September 1988	Soldan Khad, Sutlej Valley, Himachal Pradesh	WM
Rainfall-induced landslide[a]	July 1990	Neelkanth, Uttarakhand	M
Landslide-flash flood[c]	31 July - 2 August 1991	Maling, Spiti Valley, Himachal Pradesh	M
Cloudburst-landslide[c]	8 July 1993	Nathpa, Sutlej Valley, Himachal Pradesh	OM
Cloudburst-landslide[c]	24 February 1993	Jhakri, Sutlej Valley, Himachal Pradesh	
Cloudburst-flash flood[c]	11 August 1997	Chirgaon, Himachal Pradesh	M
Rainfall-induced landslide[d, e]	11–19 August 1998	Malpa and Okhimath Rishikesh-Mana, Uttarakhand	M
Cloudburst-flash flood[c]	30 July 2000	Sutlej Valley, Himachal Pradesh	M
Cloudburst-flash flood[f]	5–10 June 2000	Gangotri Glacier, Uttarakhand	OM
Cloudburst-landslide[g]	31 August 2001	Gona Village, Uttarakhand	M
Cloudburst-landslide[h, i]	16 July 2001	Phata Byung, Rudraprayag, Uttarakhand	M
Cloudburst-landslide[j]	10 August 2002	Budha Kedar, Tehri, Uttarakhand	M
Rainfall-induced landslide[a]	16 July 2003	Shilagarh, Garsa Valley, Kullu, Himachal Pradesh	M
Cloudburst-flash flood[k]	16 July 2003	PuliyaNal, Kullu, Himachal Pradesh	M
Rainfall-induced landslide[l]	23 September 2003	Varunavat, Uttarkashi district, Uttarakhand	WM
Rainfall-induced landslide[c]	July 2005	Dhanyau village, Rudraprayag, Uttarakhand	M
Cloudburst-flash flood[m]	June 2005	Phyang, Igu, and LehNalla, Jammu and Kashmir	OM
	1 August 2006		
Rainfall-induced landslide[a]	July 2007	Mandakini river basin, Uttarakhand	M
Rainfall-induced landslide[g]	July 2007	Sikkim, Darjeeling	M
	September 2007		WM
Cloudburst-landslide[g]	July 12 2007	Devpuri, Chamoli, Uttarakhand	M
Rainfall-induced landslide[n]	8 August 2009	Kuity Village, Berinag-Munsiyari, Uttarakhand	M
Cloudburst-landslide[o]	4–6 August 2010	Leh, Jammu and Kashmir	M
Rainfall-induced landslide[d, e]	18–21 September 2010	Malpa and Okhimath Rishikesh-Mana highway, Uttarakhand	WM
Cloudburst-landslide[o]	25 July 2011	Leh, Jammu and Kashmir	M
Rainfall-induced flash flood[p]	15–25 August 2010	Dokriani Glacier, Uttarakhand	M
	15–25 August 2011		
Cloudburst-flash flood[q]	3 August 2012	Asiganga, Uttarkashi, Uttarakhand	M
Cloudburst-flash flood[r]	13 September 2012	Okhimath, Uttarakhand	WM
	14 September 2012		
Cloudburst-flash flood[s]	16–17 June 2013	Kedarnath, Uttarakhand	OM
Cloudburst-flash flood[t]	16–17 June 2013	Gangotri Glacier, Uttarakhand	OM
Cloudburst-flashflood[u]	5–6 September, 2014	Udhampur, Jammu and Kashmir	WM
Cloudburst-flash flood[v]	1 July 2016	Bastadi Narula, Uttarakhand	OM

M = Monsoon (July–August), OM = Pre-monsoon (June), and WM = Withdrawal of Indian Summer Monsoon (September).
[a] Asthana and Asthana (2014); Asthana and Sah (2007); [b] Anbalagan (1996); [c] Thakur (2000); [d] Sati et al. (2006); [e] Sati et al., 2011; Rautela and Paul, 2001; [f] Haritashaya et al. (2006); [g] Naithani et al., 2002; Naithani et al., 2011; Mandal and Maiti, 2013; [h] Chaudhary et al. (2010); [i] Kumar et al. (2003); [j] Sah et al. (2003); [k] Mazari and Sah (2004); [l] Gupta and Bist (2004); [m] Thayyen et al. (2013); [n] Sarkar and Kanungo (2010); [o] Bhan et al. (2015); Juyal, 2010; [p] Kumar et al. (2014a,b); [q] Gupta et al. (2013a,b); [r] Rana et al., 2012, 2013; Islam et al., 2014; [s] Dobhal et al., 2013; Bhambri et al., 2016; [t] Arora et al., 2016; [u] Ray et al., 2015; Kumar et al., 2017; [v] Sajwan et al., 2017.

was established by fitting techniques (Kumar et al., 2014a,b; Kumar et al., 2018). The evidences of flash floods, associated with extreme rainfall events are well represented by signatures of unusual high sediment concentrations in meltwater stream. To trace this phenomenon suspended sediment sampling was carried out twice daily, i.e., at 08.00 and 17.00 h (Haritashya et al., 2006; Kumar et al., 2016a,b). The filtered samples were then packed properly at the site and taken to the laboratory for drying and weighing of the sediment samples to determine the suspended sediment concentrations (SSC) expressed in mg/l.

In order to obtain the long-distance pathways of vapor for each extreme rainfall event, backward trajectories for extreme events were produced using the HYbrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) Model (Draxler and Rolph, 2010; Yerramilli et al., 2012). We have attempted to recognize the occurrence path through wind trajectories of all the events which have been reported and their date and time of occurrence is known (Table 1). This model relies on gridded meteorological data and is used worldwide to examine the effects of vapor pathways. The backward wind trajectories were plotted using the HYSPLIT/METEX models at given altitudes for a period of 5 days or less (120 Hrs), i.e., for days prior to the actual event. North Atlantic Marine Boundary Layer Experiment (NAMBLEX) etc. are being utilized by incorporating reanalysis data. Uncertainties in the calculated back trajectories may increase over time because of insufficient ground information and non-availability of meteorological data of extreme events (Stein et al., 2015). Therefore, caution is required in trajectory interpretations, particularly on synoptic time scales.

In Himalaya, the intensity and distribution of rainfall play a key role for understanding the cloudburst phenomenon at different time scale. It is well observed that intensity and frequency of cloudburst/extreme rainfall events increase during night time (Higuchi, 1977; Singh et al., 2011; Srivastava et al., 2014). In the beginning of summer season, the rainfall occurs mostly because of convective cloud formation and during monsoon season (July, August, and September) such convection causes increase in the rainfall frequency over the region. In the present study the authors discuss the phenomenon of diurnal rainfall variability in detail. Further, we attempt to explain the active role of the Himalaya as an orographic barrier that forces the moisture bearing winds to ascend resulting in cloudburst event (Dimri et al., 2016, 2017; Dubey et al., 2013; Sundriyal et al., 2015). The precipitation is concentrated on the windward slopes, and a rain shadow is produced on the leeward side. Another aspect is the timely prediction and warning of such catastrophic local weather systems over complex Himalayan terrain, which is the first and foremost step towards mitigation of the disasters and for policy makers to minimize the impact on the society. Therefore,

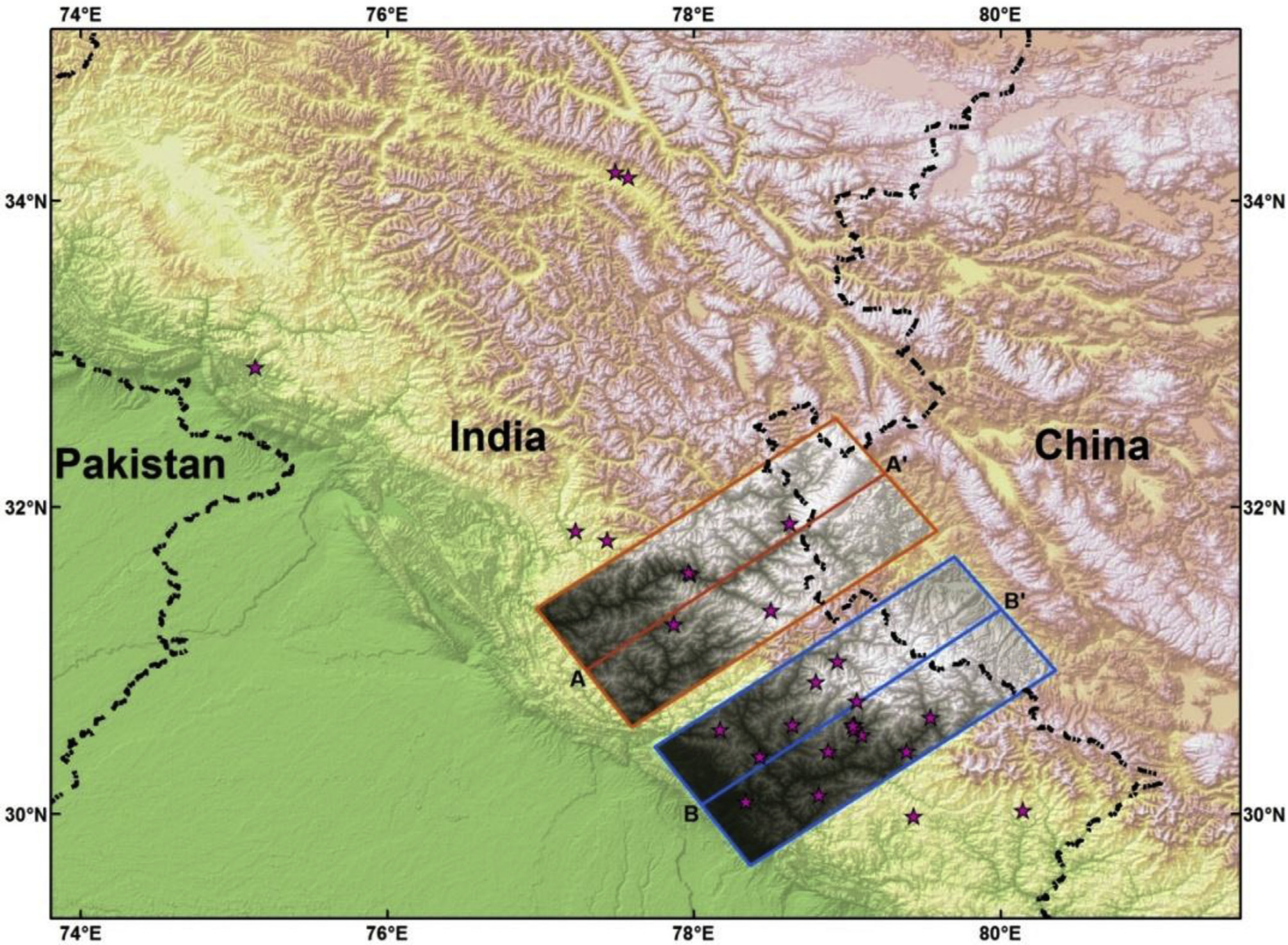

Fig. 1. Spatial distribution of cloudbursts and associated hazards in the IHR over a DEM with swath profiles for Himachal Pradesh (AA′) and Uttarakhand (BB′).

all the available models with their outputs have also been compiled and discussed with suggestions for further improvements.

3. Distribution of cloudbursts and associated hazards reported in the IHR

The IHR has experienced increased frequency of cloudburst events and associated flash floods since 1970. Massive loss to life and property take place owing to extensive flooding in the Himalayan region. In the IHR, studies on meteorological extremes have been limited or unreported, owing to non-availability of the data sets. The regional inaccessibility and sparse exposure of meteorological stations (conventional and automatic) across the IHR are the major factors making predictions of precipitation/weather extremes highly difficult. Therefore, with the limitation of hydrometeorological data sets, some case studies have been selected to snippet valuable information in the IHR that demonstrate the complex cascading processes threatening human society, infrastructure, communication network, and agricultural land (Table 1). We observe alarming situation considering that the Himalayan region has experienced increasing number of heavy rainfall events over the years causing flash floods, debris flows and landslides. Precipitation events with rainfall having high intensity (100 mm or more in one day) are not unusual in nature as reported in the Himalayan region recently (Table 2). Hence, detailed spatial representations of available records of cloudbursts including associated disasters in the IHR have been highlighted over a digital elevation model in Fig. 1. These catastrophic events were caused by heavy to very heavy rains observed during pre-, post- and syn- Indian Summer Monsoon (ISM) season.

3.1. Case studies from the Indian Himalayan glacierized catchments

The southwest monsoon generally takes about 45 days to cover the whole India from its date of onset over Kerala (India Meteorological Department). The monsoon rainfall during 2013 covered the entire country within 15 days, and the pace of progression of the ISM was fastest since 1941, i.e. one month in advance (Krishnakumar et al., 2009). This event was observed regionally over the higher altitudes of Himalaya and has been reported in various studies (Table 3). A catastrophic cloudburst event took place in the state of Uttarakhand, India during 14th–17th June, 2013. The impact of this event was observed and recorded at each of the meteorological observatories installed by Centre for Glaciology, Wadia Institute of Himalayan Geology (WIHG) near the snout of the glaciers (Chorabari and Dokriani glaciers). One of the worst hit areas was Chorabari Glacier, Kedarnath (Mandakini valley). The Centre for Glaciology, WIHG meteorological observatory at Chorabari Glacier camp (3820 m a.s.l) recorded 315 mm rain in 24 h. On 17th June morning, our hydrological site near Chorabari Glacier terminus was washed away and thus no further hydrological data was recorded on the following days. The peak discharge and SSC draining from Chorabari Glacier during the storm period 14th–17th June 2013 was recorded as 25 m^3/s and 1918.0 mg/l (Table 2), respectively, which is comparatively higher than mean discharge and mean SSC of Chorabari Glacier during the month of June or even the whole melting period (Fig. 2a). The mean monthly discharge and SSC observed during the study period (2009–2012) for the months of June, July, August and September was 2.4, 5.0, 6.3, and 3.5 m^3/s and 955.0, 1494.1, 1498.8 and 806.8 mg/l, respectively (Kumar et al., 2016a,b, 2018). This also suggests that the magnitude of meltwater discharge draining from

Table 2
Records of daily rainfall, suspended sediment concentration (SSC), and peak discharge observed from glaciated IHR during the extreme events. (*Dobhal et al., 2013).

Events	Year	Location/Region	Cumulative Rainfall (mm)	Maximum SSC (mg/l)	Peak discharge (m^3/s)	Duration (days)	Reference
Flash flood	2013	Dokriani Glacier	275	6602.0	9.3	5	Current study
Flash flood	2013	Chorabari Glacier	325*	1918.0	25	2	Current study
Flash flood	2013	Gangotri Glacier	159	–	160	2	Arora et al., 2016
Flash flood	2000	Gangotri Glacier	131.5	3599.2	120	6	Haritashya et al., 2006
Flash flood	2011	Dokraini Glacier	182.2	9798.2	~17.1	7	Kumar et al., 2014a,b
Flash flood	2012	Dokraini Glacier	259	3270.6	~13.4	2	Kumar et al., 2014a,b

Chorabari Glacier is five times higher for the particular time. Massive destruction of property, life and geomorphological changes were caused in the glaciated valley (Singh, 2014). Bhambri et al. (2016) also reported a ~5 time increase in the drainage area of Mandakini River which destroyed the motorable road and settlements at many places. The pre- and post event photographs of the Chorabari Glacier snout region and Kedarnath town are given in Fig. 3(a and b) and (c and d), respectively.

Similarly, Arora et al. (2016) reported the impact of the same event at Gangotri Glacier (Bhagirathi valley). This unusual multi–day event during the tourist season caused devastating floods, landslides, mud flows etc. resulting in massive loss of lives and property. The India Meteorological Department (IMD) linked this heavy to very heavy rainfall on the higher altitudes of Uttarakhand, Himachal and Nepal Himalaya to the convergence of southwest monsoon trough and western disturbances that led to the dense cloud formation over the Himalaya. Unusual weather events in the pro-glacial meltwater stream from Gangotri Glacier were reported by Haritashya et al. (2006) and Arora et al. (2016). These storms were concentrated upstream of Gangotri town triggering landslides/rockslides at several locations between the glacier terminus and Gangotri town. One of the major rockslides blocked the Bhagirathi River at Bhujbasa, about 3 km downstream of the Gangotri Glacier snout, creating an artificial lake at this location. Daily distribution of meltwater discharge and monthly distribution of maximum rainfall during the month of June hardly exceeds 56 m^3/s and 9.3 mm, respectively for Gangotri Glacier (Arora, 2007). However, the peak meltwater discharge was observed four times higher during the 6-day and 5-day storms and were 120 m^3/s and 160 m^3/s for the years 2000 and 2013, respectively (Fig. 2b). The total rainfall during the 6-day storm was 131.5 mm during the year 2000, while in June 2013, the area received 178 mm rainfall during 5 days. The release of water during these events generated flash floods and created havoc downstream and near the Gangotri temple during the month of June, which is unexpected. The damage and widening of the meltwater stream at Bhojbasa, Gangotri Glacier, during June, 2013 is given in Fig. 3(e and f).

In the close proximity of Chorabari Glacier, a similar flash flood took place in June 2013, during which heavy precipitation and high discharge led to the destruction of the hydrological observatory at Dokriani Glacier (Fig. 2c). The precipitation event lasted for a period of 5 days with a total rainfall of 275 mm, while the peak discharge and SSC during this event was 9.3 m^3/s and 6602.0 mg/l (Table 2). Whereas, the mean monthly discharge during the years 2010–2011 for the months of June, July and August was 2.4, 6.3, and 8.4 m^3/s, respectively and the mean monthly SSC for the months of June, July, August and September was 452, 933, 965 and 275 mg/l, respectively (Kumar et al., 2014a,b). Such flash floods at high altitudes are frequent and have rarely been reported due to lack of observational network. The authors have also reported hydrological extremes at Dokriani Glacier during the two ablation seasons (2010 and 2011). The major reason for the occurrence of these extreme events was continuous rainfall during the year 2010 that resulted into a particular rainstorm lasting for 7 days (17th to 24thAugust) accounting for 182.2 mm rainfall and evacuating high suspended sediment concentration (SSC) of 8178.1 and 9798.2 mg/l (maximum). The high intensity rainfall in 2011 precipitated for 2 days (16th and 17th August) accounting for approximately 259 mm rainfall evacuating high SSC of 3270.6 mg/l (Kumar et al., 2014a,b). The damage to the discharge gauging site at Dokriani Glacier during the extreme rainfall events are depicted by field photographs in Fig. 3(g and h). The above description of extremes and mean monthly values suggest extremely high discharge and SSC during the events of 2010, 2011 and 2013 as compared to the mean values, which cause extensive damage to infrastructure and leads to loss of lives as well in downstream areas.

Further, the average maximum, minimum and mean temperatures for the three AWS in Dokriani Glacier catchment during June, 2013 were 15.1, 7.1 and 10.3 °C, respectively. During the event the lowest maximum and mean temperatures were recorded on 17th June, while the lowest minimum temperature was on 19th June. The daily distributions of air temperatures during June, 2013 at the three stations are illustrated in Fig. 4a. Moreover, atmospheric pressure during June 2013 for three automatic weather stations installed at different altitudes in Dokriani Glacier catchment indicates a sudden drop in air pressure (Fig. 4b), resulting in the convergence of the ISM and westerlies over the region. The mean atmospheric pressure for June, 2013 in the catchment was observed to be 662.6 hPa, while the lowest atmospheric pressure was observed on 18th June (658.8 hPa). The daily variability in atmospheric pressure for the event and the month of June can be seen in Fig. 4b.

The stable isotopic composition of rain at Dokriani Glacier during the June 2013 event indicates depletion over a 5 day period and highly depleted values were recorded on 17th June 2013 (−29.7‰), which can be attributed to "amount effect" (Verma et al., 2018). Such depleted values of isotopic composition of rain have not been observed in the previous years or after. Therefore, stable isotopes can also be utilized as a proxy for understanding the phenomenon of such extreme rainfall events or cloud bursts.

3.2. Case studies from the lower Himalayan catchments

A cloudburst event that took place in the river Asi Ganga, a tributary of Bhagirathi River located downstream of Gangotri township witnessing a massive flash flood in the night of 3rd August, 2012 (Gupta et al., 2013a,b). The average daily discharge of the Bhagirathi River from 15 June to 21 September 2012 was highly abnormal. The data indicates an unusually high discharge in the rivers prior to the cloudburst and also during the cloudburst, which lasted for less than an hour. Apart from this, the regular occurrence of cloudburst event over the western fringe of the Himalaya was observed and highlighted in the region by Thayyen et al. (2013). A cloudburst in Leh (Jammu and Kashmir) occurred on 6th August, 2010. Most of such events are unreported because of lack of monitoring mechanisms in the region. However, 12.8 mm/day rainfall recorded at the nearest meteorological station at Leh did not corroborate the severity of the flood in the region but based on the satellite imagery researchers suggested that a convective system developed in the (easterly current associated with monsoon conditions) region (Thayyen et al., 2013). This catastrophic event is probably one of the worst examples in the documented history of Leh owing to its large

Table 3
Simulation studies of cloudburst and extreme rainfall events using synoptic data and different prediction models in the Indian Himalayan Region (IHR).

Events	Region	Simulation models used	Causes	References
Cloudburst	Leh, Jammu and Kashmir	Weather Research and Forecasting (WRF). The simulations in this research were carried out with the National Aeronautics and Space Administration (NASA) Unified Weather Research and Forecasting Model (NUWRF) in an effort to unify WRF with NASA's existing weather models and assimilation systems, such as Goddard Earth Observing System Model, version 5 (GEOS-5) and LIS.	Observations have led to the hypothesis that the storm that formed over the Tibetan Plateau, was steered over the Plateau's steep edge by 500 hPa winds and then energized by the ingestion of lower level moist air that was approaching from the Arabian Sea and Bay of Bengal rising up the Himalayan barrier.	Kumar et al., 2014a,b
Cloudburst	Leh on August 05, 2010	The numerical mesoscale model Weather Research and Forecasting (WRF) has been used simulating the cloudburst event of Leh on August 05, 2010, so as to capture the main characteristics of various parameters associated with this localized mesoscale phenomenon. The model has been integrated with four nested domains keeping Leh and its adjoining area as center.	Cumulus convective clouds are developed deeply on a localized area that has a capability of giving enormous rainfall amount over a limited horizontal area, within a short span of time. It represents cumulo-nimbus convection in conditions of marked moist thermodynamic instability and deep, rapid dynamic lifting by steep orography	Kumar et al., 2012.
Cloudburst	Leh on August 05, 2010	High resolution nested WRF model (9 and 3 km) is used simulating the Leh cloudburst event. The results from the 3 Km WRF experiment show peak intensity between 1500 and 1800 UTC as indicated by the Tropical Rainfall Measuring Mission (TRMM) satellite based precipitation estimates.	The cross section analysis suggests that the cloudburst evolved in a deep humid layer of flow from the northwest of the Leh capped by relatively cold and dry flow from the east and southeast. This capping seems to inhibit the release of instability. The instability trigger seem to have come from the cloud cluster that moved from Nepal	Ashrit, 2010
Cloudburst	Kedarnath, 15–16 June, 2013, Uttarakhand	Weather Research and Forecasting (WRF) High spatial resolution (2 km) model was used to simulate the Kedarnath heavy rainfall event over Uttarakhand region of India during 16–17, June 2013.	The westerlies and the monsoon system virtually locked over Uttarakhand and neighbouring regions during this period. The Uttarakhand episode was unique in that the line of convergence of the two weather systems was nearly stationary for hours at a time caused by orographic focusing of convective cell activity over limited region resulting in huge accumulation of rainfall over the northwestern Himalayan region causing widespread flooding.	Kumar et al., 2016a,b
Cloudburst	Kedarnath, 15–16, 2013, Uttarakhand	The daily meteorological parameters such as wind velocity, wind pattern, pressure, total cloud cover, surface temperature, relative humidity, surface precipi-tation rate and surface convective precipitation rate with 0.5 grid resolution were obtained from Climate Forecast System Reanalysis (CFSR) data developed by NOAA's National Center for Environmental Prediction (NCEP) for the selected region.	The convergence of the Southwest monsoon trough and westerly disturbances over the region was observed. A low-pressure zone with very high cloud cover (60–90%) and relative humidity (70–100%), associated with low ($< 4\,m\,s^{-1}$) wind velocity, are observed over the Kedarnath region during 15–17 June. .	Singh et al., 2015
Widespread very heavy to extremely heavy rainfall episodes in Himalaya	16–18 June, 2013 Uttarakhand	The various dynamical and thermodynamical parameters that are analyzed for the heavy rainfall event derived from the IMD operational WRF model (27 km resolution) daily analysis fields. For accurate analysis of the cloud structure and distribution, the observations of the Doppler radar network of IMD are used for analysis.	During the period, a western disturbance moved across North India from west to east. The westerlies and the monsoon system virtually locked over Uttarakhand and its neighbouring regions during the period and there was moisture feeding both from the Arabian Sea and Bay of Bengal.	Kotal et al., 2014
Cloudburst	3, August 2012 Uttarkashi	Numerical simulations were performed using the Weather Research and Forecasting (WRF) model, configured with a single domain at 18 km resolution.	The results indicate that two mesoscale convective systems originating from Madhya Pradesh and Tibet interacted over Uttarkashi and, under orographic uplifting in the presence of favorable moisture condition resulting in this cloudburst event.	Chaudhuri et al., 2015
Cloudburst	June 14–17, 2013, Uttarakhand	Observational aspects of this event have been explored using surface, satellite and reanalysis data. Precipitation features have been explored using TRMM satellite in conjunction with Automatic Weather Station and Automatic Rain Gauge Station data. The ERA interim dataset has been used to explore prevalent synoptic conditions.	The southward penetration of mid-latitude westerlies and their interaction with monsoon current are harbinger of intense rainfall activity over northern and central India. Results reveal that interplay between movement of monsoon trough resulting into low-level convergence and strong upper-level divergence owing to intrusion of mid-latitude westerly trough resulted in heavy rainfall activity over Uttarakhand.	Ranalkar et al., 2016
Cloudburst	Kedarnath, 16–17, June, Uttarakhand, 2013	WRF model was used with triple-nested domain for simulation at finer resolutions; this high-intensity precipitating event is analyzed.	The very early migration of monsoon trough (MT) towards northern India and its interaction with an incoming western disturbance (WD) formed a transient cloud system that led to extreme precipitation.	Chevuturi and Dimri, 2015

(*continued on next page*)

Table 3 (*continued*)

Events	Region	Simulation models used	Causes	References
Cloudburst	September 15, 2011, Delhi and neighborhood area.	Mesoscale model (ARPS) with real-time assimilation of Doppler Weather Radar data has been operationally implemented in India Meteorological Department (IMD) for real-time newscast of weather over Indian region. Three-dimensional variation (ARPS3DVAR) technique and cloud analysis procedure are utilized for real-time data assimilation in the model.	In the case of cloudburst event, the model is able to capture the sudden collisions of two or more clouds during 09–10 UTC. Rainfall predicted by the model during cloudburst event is over 100 mm which is very close to the observed rainfall (117 mm). The model is able to predict the cloudburst with slight errors in time and space.	Srivastava and Bhardwaj, 2014
Cloudburst	Shillagarh village, 16 July 2003. Himachal Pradesh	We examine the fidelity of MM5 model configured with multiple-nested domains (81, 27, 9 and 3 km grid resolution) for predicting a cloudburst event with attention to horizontal resolution and the cloud Microphysics parame-terization.	The MM5 model predicts the rainfall amount 24 h in advance. However, the location of the cloudburst is displaced by tens of kilometers.	Das et al., 2006
Intense heavy precipitation event	13–14 September 2012. Rudra-prayag and Ukhimath, Uttarakhand	Present dynamical fields associated with this event, Weather Research and Forecasting (WRF version 3.4) model was used to understand the processes related to the severe storm event for the 3 km grid spacing domain.	Incursion of moist air, in the lower levels, converges at the foothills of the mountains and rise along the orography to form the updraft zone of the storm.	Chevuturi et al., 2015
Cloudburst and flash floods	4–6, August 2010, Leh, Jammu and Kashmir	Hydrological evaluation: Indirect flash flood peak discharges may be estimated by using based on Manning's equation, (HEC-RAS), two-dimensional depth-averaged hydraulic model (TRIM2D or SRH2D). Atmospheric processes evaluation: A triple nest simulation (27, 9 and 3 km) is performed using Advanced Research Weather Research and Forecasting (WRF) modelling system.	Independent estimate by the atmospheric process model and the hydrological method shows storm depth of 70 mm and 91.8 (± 35%) mm, respectively, in catchment scale. Model simulates precipitation amount which is in very close correspondence with the observed rainfall over the region.	Thayyen et al., 2013
Extreme rainfall event	13 September 2012, Uttarakhand	Operational regional weather forecast model COSMO at a convection-permitting resolution of 2.8 km was used to simulate this event.	Convergence of moisture over the north-western part of India, leading to an increase of potential instability of the air mass along the valley recesses, which is capped by an inversion located above the ridgeline; and strengthening of the north-westerly flow above the ridges, which support the lifting of the potentially unstable air over the protruding ridge of the foothills of the Himalaya.	Shrestha et al., 2015
Extreme rainfall	16–18, June, 2013, Uttarakhand	A version of the WRF3.4 model is used in this study. This event is addressed via sensitivity studies using a cloud resolving non-hydrostatic model with detailed microphysics.	We show that a moist boundary layer near the Bay of Bengal leads to moist rivers of moisture where the horizontal convergence confines a large population of buoyancy elements with large magnitudes of buoyancy that streams towards the region of extreme orographic rains.	Krishnamurti et al., 2017
Extreme rainfall	16, June, 2013, Uttarakhand	The study also examines the skill of an ensemble prediction system (EPS) in predicting the Uttarakhand event on extended range time scale.	It is found that a monsoonal low pressure system that provided increased low level convergence and abundant moisture, and a midlatitude westerly trough that generated strong upper level divergence, interacted with each other and helped monsoon to cover the entire country and facilitated the occurrence of the heavy rainfall event in the orographic region.	Joseph et al., 2015
Extreme rainfall	16–18 June, 2013, Uttarakhand	The National Centers for Environmental Prediction– National Center for Atmospheric Research reanalysis data were used on a 2.58 3 2.58 grid to investigate the large-scale synoptic features	Rather, an eastward-propagating upper-level trough in the westerlies extended abnormally far southward, with the jet reaching the Himalayas. The south end of the trough merged with a monsoon low moving westward across India.	Houze et al., 2017
Extreme rainfall	16-18, June, 2013, Uttarakhand	National Centre for Medium Range Weather Forecasting based global model (NCUM) with 17 km horizontal resolution is examined for the synoptic features associated with the heavy rainfall events during 2016 summer monsoon over central India.	It is seen that the stronger winds and associated moisture transport from Arabian Sea and Bay of Bengal to the Indian land region leading to the extreme rainfall events	Shrivastava et al., 2017
Extreme rainfall	16-18, June, 2013, Uttarakhand	Daily zonal, meridional and vertical wind data at 12 GMT from European Centre for Medium Range Weather Forecasts (ECMWF) interim re analysis (ERA-interim) with resolution 0.75° x 0.75°	The mid-latitude westerlies shifted southward from its normal position during the intense flooding event. The southward extension of subtropical jet (STJ) over the northern part of India was observed only during the event days and its intensity was found to be increasing from 14th to 16th June.	Xavier et al., 2018
Extreme rainfall	16-18, June, 2013, Uttarakhand	Climate Forecast System model version 2 (CFSv2) developed by National Centre for Environmental Prediction (NCEP).	The models were able to predict the progression of ISM over the Indian region and the subsequent intraseasonal oscillations (active and break phases).	Borah et al., 2015

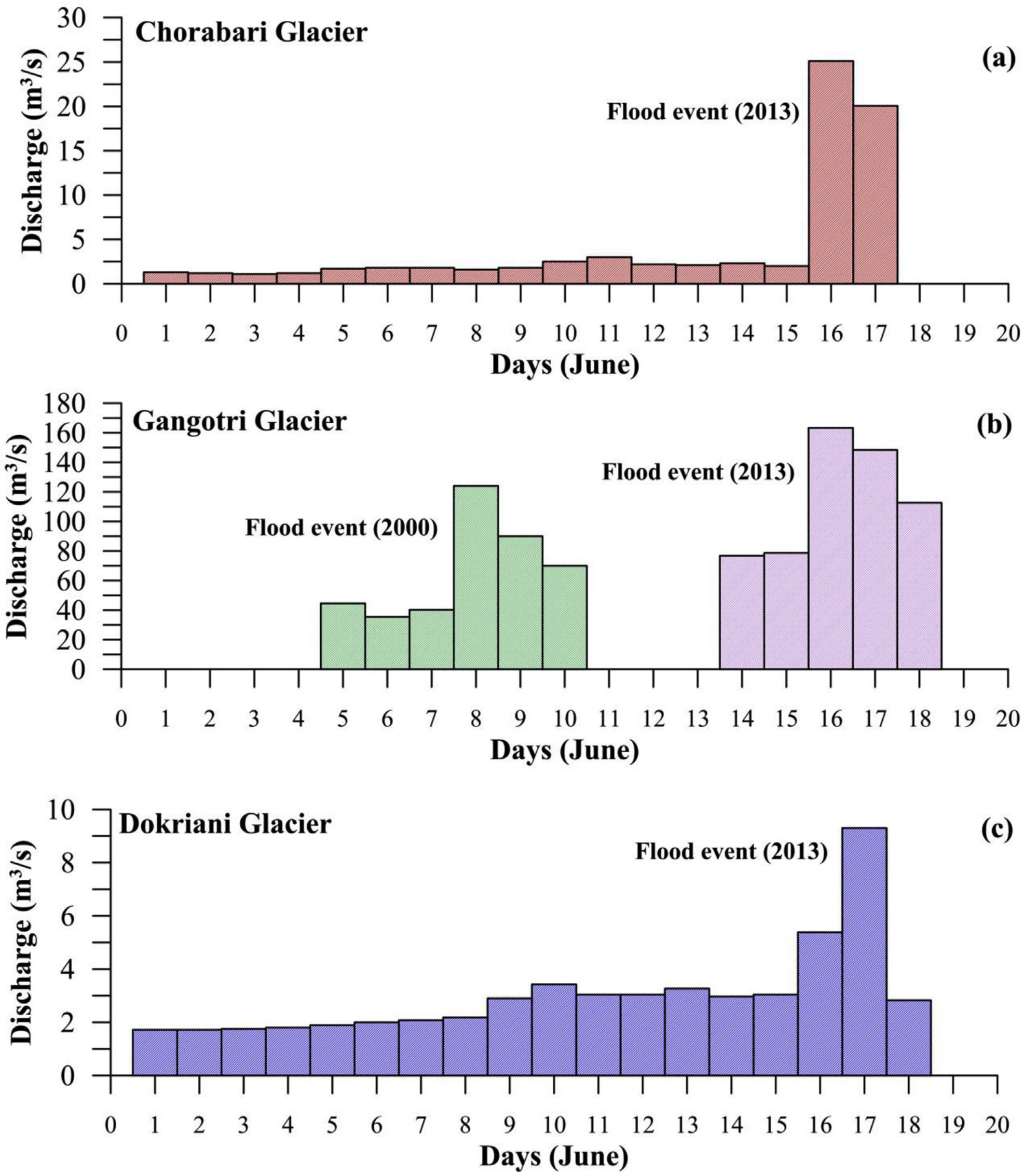

Fig. 2. Records of daily meltwater discharge observed during the extreme events in the month of June for (a) Chorabari, (b) Gangotri (Haritashya et al., 2006; Arora et al., 2016) and (c) Dokriani glaciers in the IHR.

extent and significant erosion within a short span of few hours. The event was highly localized and only the streams on the right bank of the Indus River responded to the event, while the left bank remained unaffected.

4. Orographic distribution of cloudburst events in the IHR

Climate of the Indian subcontinent is governed by the summer (June to September) and winter monsoons (November to March). The climate of the Himalaya greatly varies and differs across the region on account of great variations in altitude and rugged topography. In summers, the area receives rainfall from southwest monsoon winds while in winters, westerly winds from the Mediterranean cause snowfall and rainfall. Mountains act as barriers and force moisture bearing winds to ascend resulting in orographic effects on precipitation (Prudhomme and Reed, 1998). The precipitation is concentrated on the windward slopes, and a rain shadow is produced on the leeward side (Singh and Kumar, 1997). The ISM produces heavy rainfall on the southern slopes of the Himalaya, whereas the northern Himalayan ranges are deprived of ISM precipitation (Singh et al., 2005). Altitudinal variations in rainfall make the rainfall distribution more complex in the mountainous regions. A number of studies have been carried out to understand variability in precipitation with altitude in different mountainous regions of the world (Marquínez et al., 2003; Arora et al., 2006; Shrestha et al., 2000). Based on the relief of a mountain, there may be a continuous increase in precipitation with altitude that begins to decrease above a particular height (Singh et al., 1995; Singh and Kumar, 1997). Some studies show that the rainfall trend goes on increasing with altitude up to about 2500 m a.s.l. and then starts decreasing. Studies related to the rainfall characteristics during the monsoon season in the high mountain areas of the Nepal Himalaya suggests that rainfall decreases with altitude in the range from 2800 to 4500 m a.s.l. (Higuchi, 1977).

In the present study two longitudinal profiles AA′ and BB′ were constructed to represent the topographic distribution of extreme events in Himachal Pradesh and Uttarakhand states, respectively across the Himalayan range. The locations of available points have been plotted

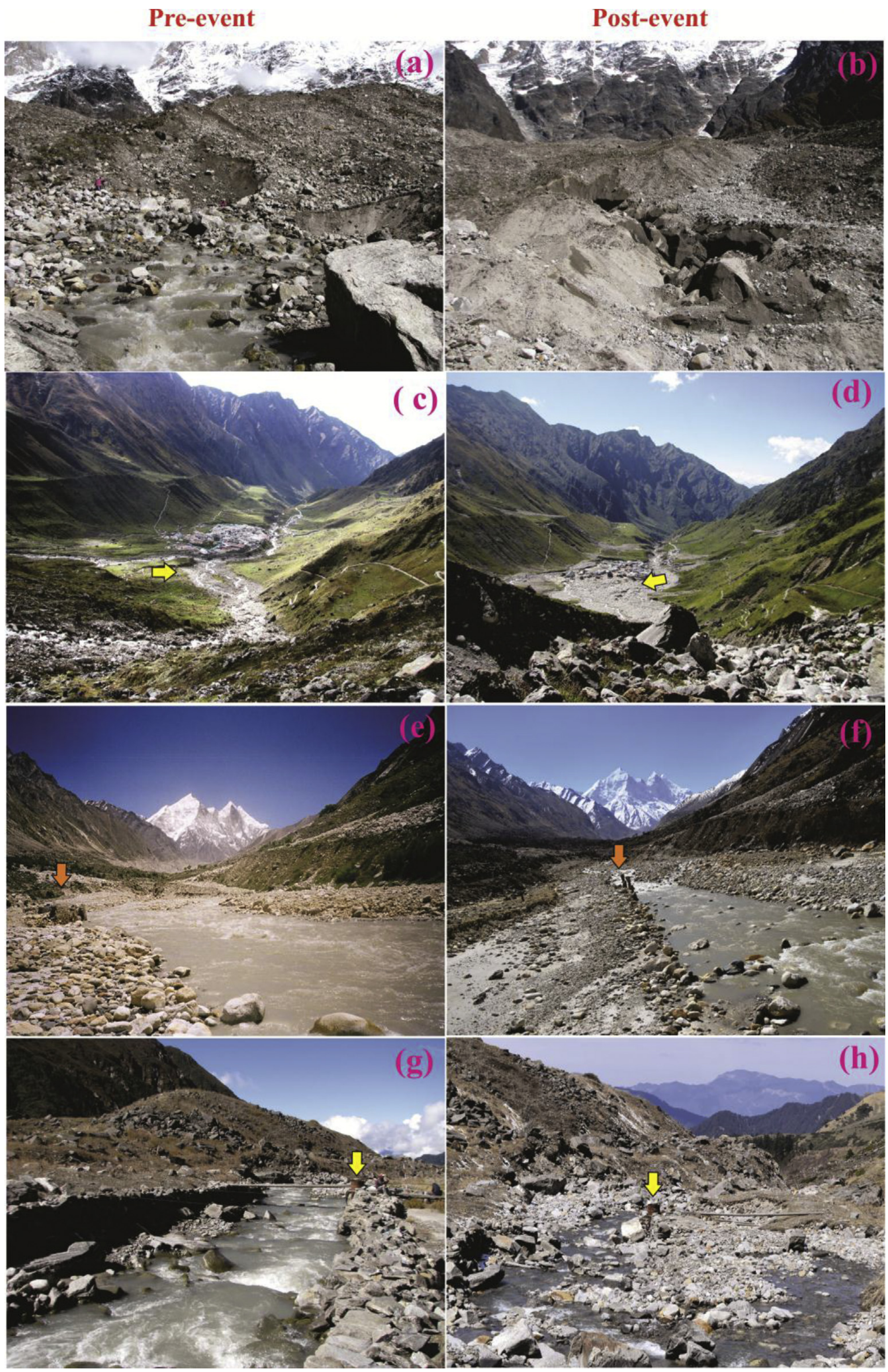

Fig. 3. Photographs of pre- and post-flood events causing morphological changes in Chorabari Glacier (a, b); Kedarnath town (c, d); meltwater streams of Gangotri Glacier (e, f) and Dokriani Glacier (g, h).

over the profiles (Fig. 5), while some points are outside the swath profiles, which have also been discussed separately. From the present distribution point of view, we concluded that most of the events recorded highest rainfall intensity in the Himalaya is orographically situated on the windward side (Fig. 5a and b). Also, most of the events occur in the deep closed valleys. The events in Himachal Pradesh (AA′) are mostly confined to 60–120 km from the Himalayan front and below 3000 m a.s.l. (Fig. 5a), while in Uttarakhand (BB′) the events are distributed throughout i.e. from 10 to 150 km from the Himalayan front and at different altitudes (Fig. 5b). Further, analysis suggests that consecutive high intensity rainfall causes cloudburst like situations (Table 2). Consequently, we can conclude that during summer season, the abnormal rainfall pattern has been observed towards the onset or at the withdrawal of the monsoon season that results into cascading

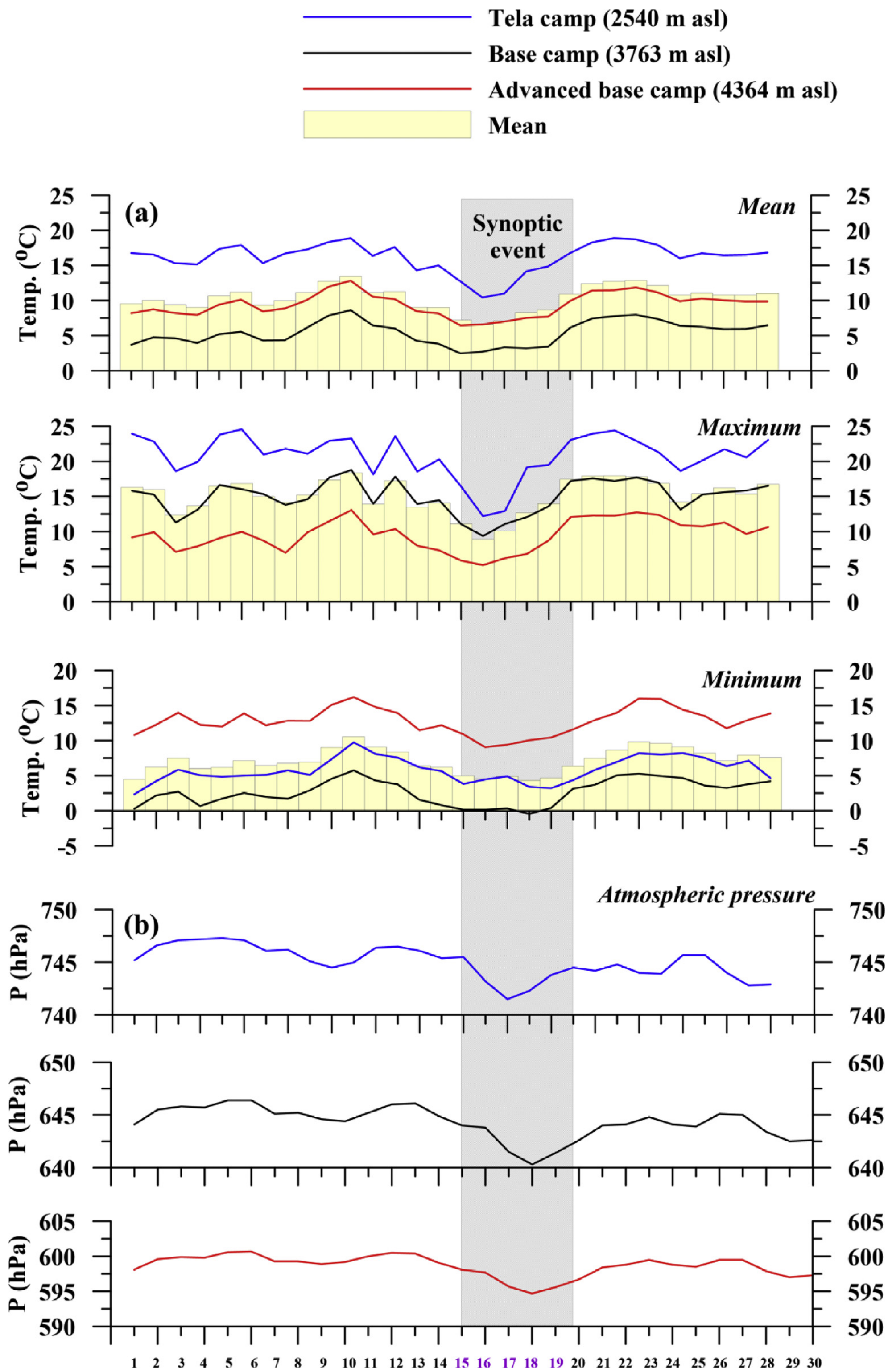

Fig. 4. Distribution of air temperature and atmospheric pressure (P) at different elevations within the Dokriani Glacier catchment during June 2013.

effects such as landslides and flash floods in the IHR (Table 1). The present analysis indicates that the trajectory of the ISM along with the influence of local moisture are important factors which drive the orographic precipitation and are responsible for generating cloudburst like events (Fig. 6).

5. Diurnal variability in precipitation over the Himalayan range

Diurnal rainfall variability over the Himalayan range helps in analyzing temporal changes in rainfall intensity and its distribution. At the onset of the summer season, rainfall occurs mostly because of convective cloud formation. The approaching monsoon season (July, August, and September) causes increase in the rainfall frequency driven by combination of local convective activity and the monsoonal

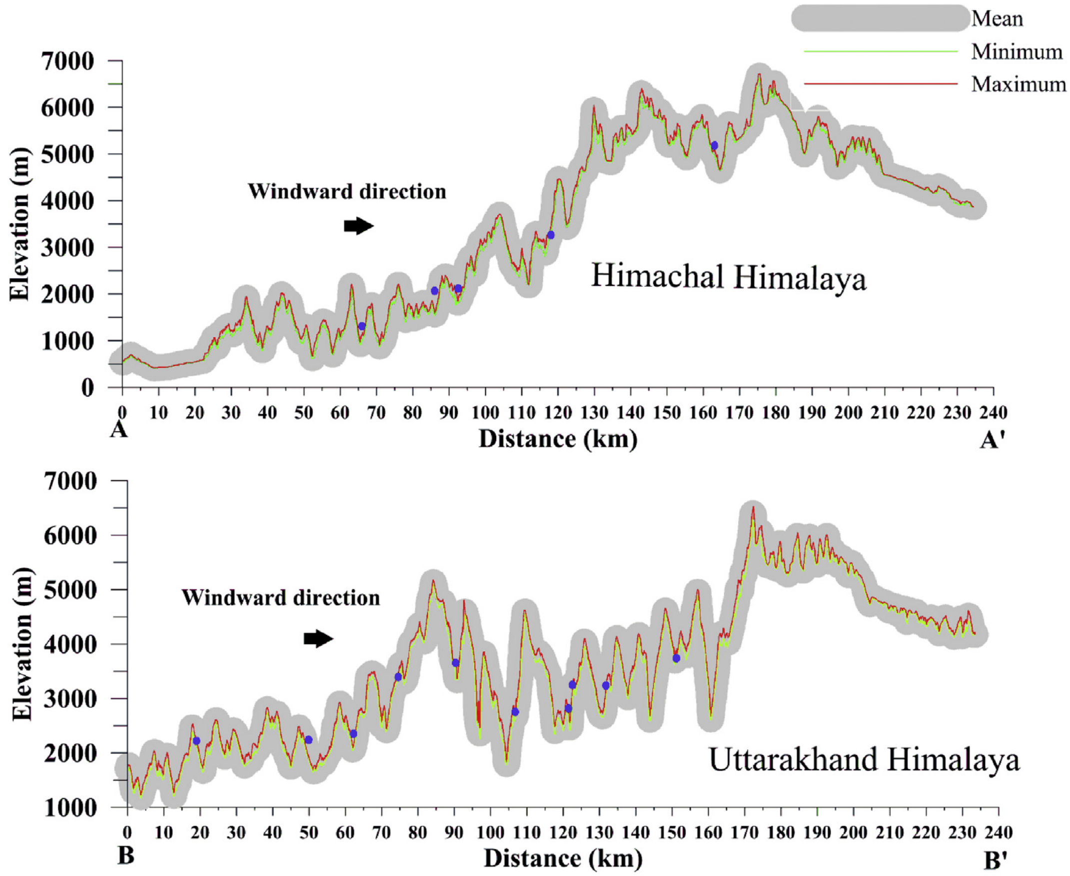

Fig. 5. Spatial distribution of cloudbursts and associated hazards over the longitudinal swath profiles extracted from the DEM in the IHR. (Blue dots represent the locations of cloudbursts and associated hazards). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

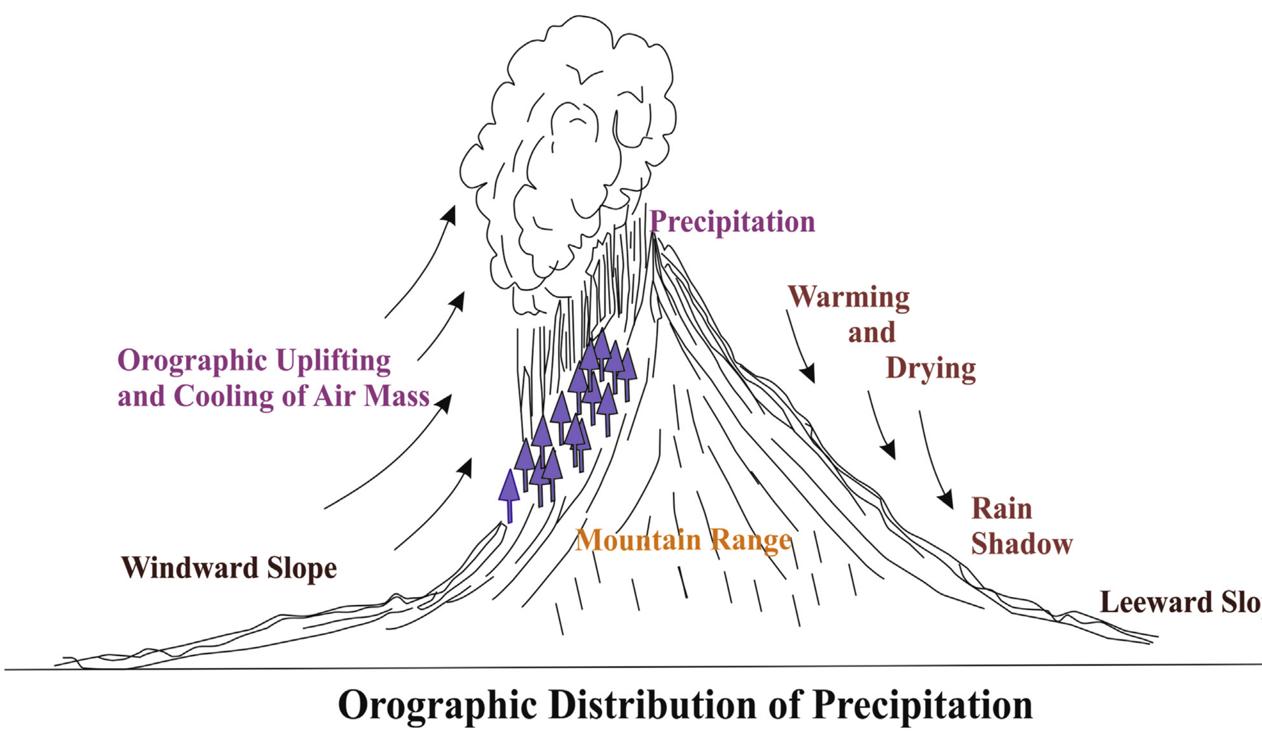

Fig. 6. Graphical representation of the process of orographic lifting of air masses in the Himalayan region.

influence in the region. The trend of rainfall occurrence shows that late evening or early morning was the most probable time for the occurrence of heavy rainfall and cloudburst. We find an interesting instance of cloudburst events that mainly took place during the night time and impacted the downstream areas situated at an altitude of < 2500 m a.s.l.. The Himalayan range is also unique for being too hot in the day time and too cold in the nighttime especially in the summer indicating high diurnal temperature variability.

In the light of the present status, large scale cloudburst and associated flash floods inundate Uttarakhand Himalaya. Furthermore, the frequency of diurnal variability in rainfall at higher altitudes of the Uttarakhand Himalaya is high either in the evening or early morning and generally the least rainfall events were recorded between 0800 and 1400 h, except in August and September (Singh et al., 2005, 2007; Srivastava et al., 2014). Srivastava et al., 2014 reported that 71% of the total rainfall occurs during the nighttime in Uttarakhand Himalaya. Similarly, in the Nepal Himalaya, Higuchi (1977) observed 60% of the total precipitation at nighttime over Rikha Samba Glacier causing variations in melting processes during daytime and nighttime. Therefore, we can conclude that, most of the cloudburst events occur during the night and early morning.

6. Development of wind trajectories of selected extreme events during pre-, post- and peak ISM

In the present study, we can observe that the extreme events are distributed throughout the ISM season. Less but intense frequency of extreme events was observed during the pre- and post-monsoon seasons (Table 1). Therefore, development of wind trajectories for such events act as a valuable tool for inferring the source of moisture to the region (Soderberg et al., 2013; Pérez et al., 2015; Kumar et al., 2018). The backward wind trajectories were plotted for the selected events with their occurrence during pre-, post- and peak monsoon time (Table 1). A trajectory path was calculated for each event with the date and time of occurrence of the particular event (Fig. 7). We initially examined the associated trajectories quantitatively and found that several air parcels were mixed and transported during the event. This enabled us to define the geographic extent of the source region for each extreme event using trajectory paths determining the relative importance of long and short distance moisture transport. Individual case studies such as these may give an insight into specific events, but lack of replication makes it difficult for any general conclusions. To achieve this, one must analyze a larger number of extreme events in one region identifying the patterns. Therefore, archived events from Uttarakhand and Himachal Pradesh have been taken up for the trajectory analysis in Fig. 7.

The temporal and spatial patterns of extreme rainfall events in the Himalayan region are indicative of governing hydrometeorological and atmospheric processes. The precipitation occurring during pre-monsoon (May, June) and post-monsoon (September end, October) or retreating monsoon seasons is mainly caused by mixing of moisture from different sources, whereas the moisture source during July and August are derived from the ISM. The backward wind trajectories plotted for the extreme rainfall events in Uttarakhand and Himachal Pradesh indicate that the major source of extreme events is from the ISM, while the local moisture interplays with the Westerlies during pre- and post-monsoon seasons, which are lifted orographically leading to cloudburst events. The representative backward wind trajectory for the events during the onset of the monsoon is in Fig. 7a, while the events during the monsoon are in Fig. 7b–j and (k and l) depict the events during withdrawal of monsoon.

7. Prediction of extreme rainfall events using numerical weather prediction (NWP) models

In recent times, various prediction models have been successfully configured at high spatial resolution for simulating the heavy rainfall events over the Uttarakhand region (Kotal et al., 2014; Shrestha et al., 2015; Chaudhuri et al., 2015; Kumar et al., 2016a,b; Chevuturi and Dimri, 2015; Das et al., 2006). Timely prediction and warning of such catastrophic local weather systems over complex Himalayan terrain are the first and foremost steps towards mitigation of disasters and for policy planners to minimize the impact of such catastrophes. Rainfall is probably the most important parameter predicted by numerical weather prediction (NWP) models (Table 3), though the skill of rainfall predictions is poorest compared to other parameters, e.g., temperature and humidity (Srivastava et al., 2014). Since, rainfall impacts society directly or indirectly, the accuracy and skill of rainfall prediction at varying spatiotemporal scales are strongly desirable. Rainfall forecast from the NWP models have been improved over the last few decades with continuous progress in both numerical models and data assimilation techniques. Several attempts in the IHR have been made to predict such events using NWP and satellite derived products (Table 3). However, the prediction of extreme localized rainfall events over high complex terrain using NWP models remains a challenge because of insufficient model resolution, poor representation of orographic effects over complex terrain, lack of good quality data over remote areas and insufficient land surface parameterization. Also, the present status of all predictive models and satellite products can be better utilized in conjunction with ground based information that can help in selecting potential sites which may be vulnerable to cloudburst occurrences. The authors have compiled most of the studies by researchers in Table 3, which simulated devastating events such as Kedarnath in June 2013 and Leh in August 2010. All these studies have been carried out using post-facto ground based data, i.e. none of the studies could predict such events prior to its occurrence. This is owing to the fact that most of the prediction models are dependent for validation from the ground based observations.

8. Conclusions

- The available meteorological and field data sets do not appear to be adequate in serving as a stand-alone product. However, the results should be very useful and reasonable when combined with the maximum number of rain gauges deployed at different climatic zones in the Himalaya. The rainfall data at hourly scale are still unique in terms of their distribution frequency and analysis of magnitude during extremes. Further, a detailed inventory of all the extreme events including cloudbursts, landslides, flash floods, avalanches etc., should be prepared with all attributes like location, elevation, etc., needs to be prepared.
- Review suggests that every cloudburst event has a unique frequency distribution in terms of its intensity duration. Rainfall is highly variable in the higher altitudes over Himalaya. There is no significant relationship observed in the amount of rainfall and the occurrence of the cloudbursts. The regional topography has a large influence on the distribution of precipitation i.e. on windward and leeward slopes. For example, Gangotri Glacier received less amount of rainfall as compared to Dokriani Glacier in the same river basin (Bhagirathi basin) and altitude during the regional event of June 2013. However, the impact of the event was considered identical.
- Spatial distribution of cloudburst events shows that the windward side of the Indian Himalayan Region (IHR) is generally conducive for precipitation and generating cloudburst, while the leeward side is warmer and drier. As the air moves down the opposite side of the mountain after losing its moisture it warms up.
- Majority of the events occurred during the pre-, post- and peak monsoon seasons and mostly at night, impacting villages at lower altitudes. This is due to the fact that the IHR receives maximum rainfall amount during the nighttime especially in the Uttarakhand Himalaya.
- Most of the peak monsoon events have their moisture source in the Arabian Sea, while those during the pre- and post-monsoon seasons

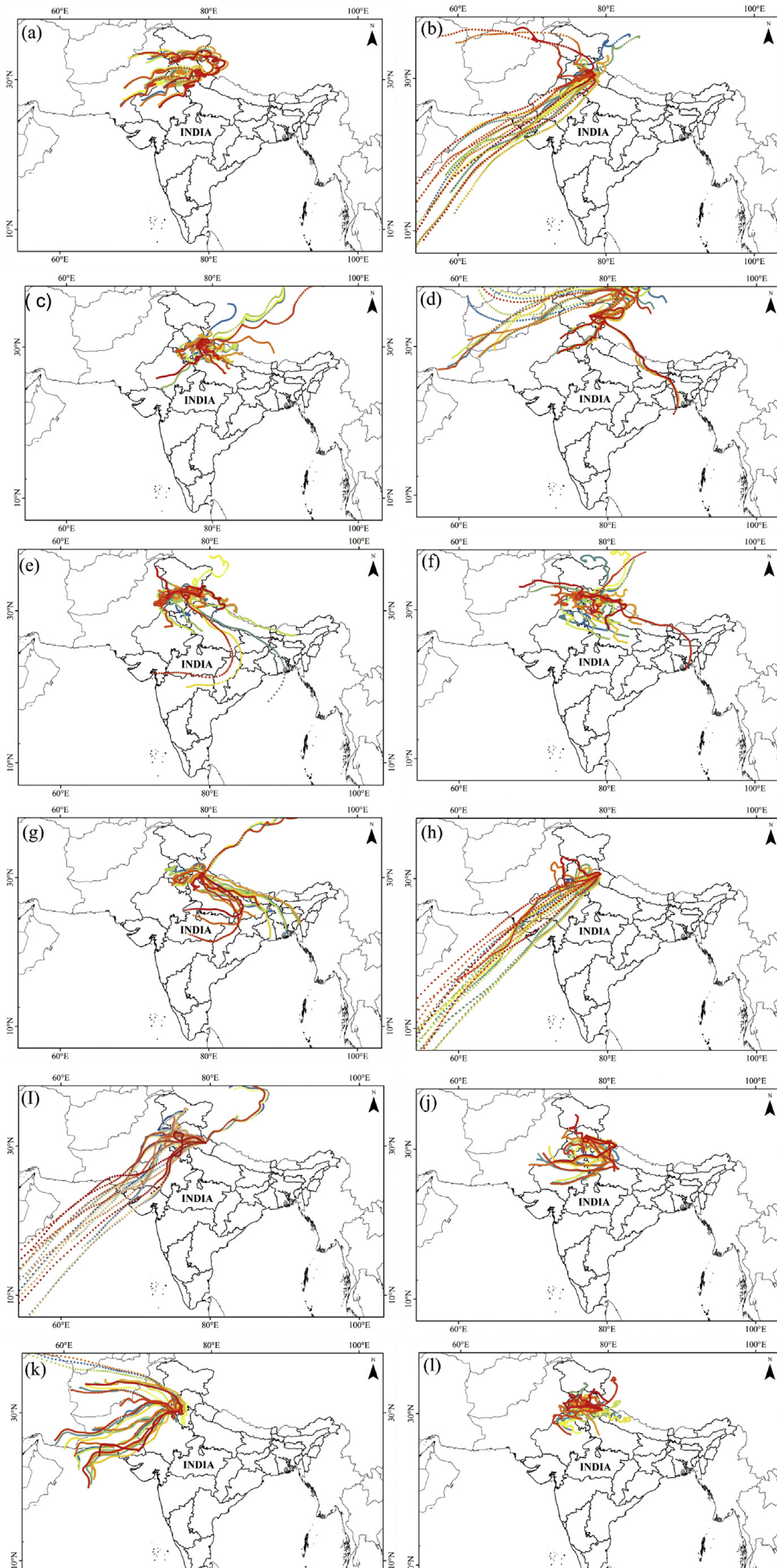

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Fig. 7. Backward wind trajectories of cloudburst events recorded during onset of monsoon at Kedarnath (a); during peak monsoon at Gohna (b), Budha Kedar (c), Leh (d), Maling (e, f), Malpa (g), Phata Byung (h), Birahi River (i), and Shilagarh, Kullu (j); during withdrawal of monsoon at Udhampur (k) and Okhimath (l) observed in the IHR.

have influence from the local moisture sources as well as from the mid-latitude westerly and polar jets.

- The most prominent feature observed in relation to the cloudburst events during pre- and post-monsoon seasons is that the Westerlies along with regional moisture are dominant during this period. The moisture laden Westerly winds descend over the low pressure region equalizing the air pressure and combine with the local moisture, which are orographically lifted and cause cloudburst and consequently flash floods.
- The large scale features that are conducive for occurrence of severe thunderstorms associated with cloudburst are predictable two to three days in advance. However, the specific location and cloudburst timing can be predicted in NOWCAST mode only, i.e., a few hours in advance, when the event genesis has already commenced.
- For detecting these sudden developments, a network of automatic weather stations (AWS) along with real-time monitoring and Doppler Weather Radar (DWR), a powerful tool for time and location specific prediction of cloudburst, should be deployed. Coupled with satellite imagery this can prove as useful input for extrapolation of cloudbursts in the IHR.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.polar.2018.08.004.

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