# Cloudbursts in Indian Himalayas: A Review

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## Abstract

Cloudbursts in and around the southern rim of the Indian Himalayas are elusive in terms of their position and time of occurrences. Most of the reported cloudbursts are in the interior of the Himalayas and hence their observation itself is limited. Most of these events are reported once their affect in terms of loss to life and property is experienced in the downstream habitats. In addition, they are mostly associated with flash floods as an impact of the torrential precipitation. The principal understanding of the cloudburst is associated with sudden heavy deluge of precipitation in very less time interval over a very small area. Except this understanding and India Meteorology Department (IMD) definition of >100mm/h precipitation over a geographical region of approximately 20-30 $Km^2$, nothing much else is known about these events. There are a very few studies carried out on understanding of these events. Present paper synthesizes the available information and research on cloudburst events and tries to define it based on associated dynamics, thermodynamics and physical processes leading to a cloudburst event. Thus in the present work, characterizations and impacts of cloudburst leading from precipitation to dynamical to thermodynamical to large scale forcings to orographical forcings to followed geomorphology to impacts are intertwined to present comprehensive portray of it.. Most of the cloudburst events are seen occurring in the elevation range of 1000m to 2500m within the valley folds of the southern rim of the Indian Himalayas. Apart from some of the large scale flow shown by few of the studies, it is found that cloudburst events are convectively triggered followed by orographically locked systems. These intertwined mechanisms lead cloudburst events to form. Amiss of any one of these mechanisms will not lead the cloudburst mechanism to form. These interactions in the present paper established the vagaries associated with the cloudburst events.

**Key Words:** Cloudburst, convective trigger-orographic locking, valley folds, Indian Himalayas

## 1. Introduction

In the recent decades vagaries associated with ‘cloudburst’ events are frequently reported in and around the southern rim of the Indian Himalayas. Most of these cases are associated with unexpected heavy precipitation. The Himalayan orography with its steep and unstable inclines forms a perfect platform for such a cloudburst event to lead to flash floods or landslides. Predicting the location, amplitude and magnitude of such catastrophic events in advance remains a challenge. Various researchers have worked on case base studies associated with the cloudburst events right from reconstruction from geomorphic signature of the hindcast case (Hobley et al., 2012) to the observations studies (Gupta et al., 2013; Juyal, 2010) and to the modelling studies (Thayyen et al., 2012; Kumar et al., 2012). Rasmussen and Houze (2012) and Kumar et al. (2014) have extensively provided signature of large scale flow and topographic interactions associated with Leh cloudburst event, 2010. With modelling efforts, Das et al. (2006) have provided an insight of a cloudburst event and associated dynamical interactions with the topography. Upadhyay (1995) suggested most of these events in mountainous regions are associated with cumulonimbus or thunder clouds. In a very short time span over a much localized area heavy downpour ranging from 200 – 1000 mm/h occurs in these events (Deoja et al., 1991). Corresponding droplet size ranges from ~4 – 6 mm with fall speed of ~10 m/s (Singh and Sen, 1996). Joshi (2006) based on four years precipitation analysis over the Ukhimath region of the central Himalayan has shown increase in such extreme events. Gupta et al. (2013) have studied the cloudburst event of 3 Aug 2012 occurred over the Asi Ganga, a tributary of the Bhagirathi river, in Garhwal Himalayas. This study remains limited to associated flash flood, geomorphic details and impacts etc. on the society. But the study mentions that the orographic architecture of the mountain regions makes them ideal for generating localized cyclonic storms in the confines of a closed valley which lead to cloudbursts. Sah and Mazari (2007) reported occurrence of most of these cloudburst events mainly during the monsoonal periods, restricting over mainly headwater areas of closed tributaries/valleys. Joshi (1997) has reported damage in the two of the river basins in Garhwal Himalayas due to cloudburst occurrence during 1997 monsoon. In addition he provided people's perspective, mechanism and impact of cloudburst over the Central Himalayas. Bhandari and Gupta (1985) has reported cloudburst events and associated impacts over the northeast Indian Himalayas. Joshi and Makhuri (1997) have illustrated on impacts due to one of the cloudburst occurred in central Himalayan region in 1992. Juyal (2010) has reported on sight evolution of Leh cloudburst of 6 Aug 2010. Das et al. (2006), probably, first time provided the dynamical structure, physical processes and orographic interactions associated with one of the cloudbursts occurred over the central Himalayan region on 16 Jul 2003. Using modelling strategies, they concluded that *'low-level convergence of southeasterlies and northeasterlies along the foothills coupled with vertical shear in wind and orographic uplifting leading to a short-lived, intensely precipitating convective storm (cloudburst)'*. The paper also provides a general definition of a cloudburst event (as also adopted by IMD) as *a weather phenomenon with unexpected precipitation exceeding 100mm/h over a geographical region of approximately 20-30 $Km^2$*. Dimri (2013), however, indicated status on early warning systems associated with such hazards as early as in 1894. Bhan et al. (2004) have objectively summarised that most of the cloudburst events occur during monsoon season with higher frequency during the months of Jul and Aug. Bhan et al. (2015) further suggested these events to be associated with westward moving cyclonic circulations in middle troposphere (~500hPa) over the Tibet-Ladhak region during active monsoon conditions. Sikka et al. (2015) and Ray et al. (2015) have also suggested the interaction of low level westward moving monsoonal systems and eastward moving mid-tropospheric westerly trough as one of the main causes of catastrophic floods over Uttarakhand in 2013 and Jammu & Kashmir in 2014, but have ruled out the possibility of cloudburst based on IMD's definition. This established the fact that such positioning and timing is crucial for occurrence of cloudburst events over the Himalayan region.

In case of heavy deluge events associated with mesoscale convection occurred over Indian sub-continent various researchers have provided dynamical understanding. Semwal and Dimri (2010) have demonstrated role of microphysics parameterization during the Mumbai deluge. While studying the same case with high-resolution Weather and Research Forecast (WRF) modelling framework, Kumar et al. (2008) have shown mesoscale vortex over the Mumbai resulting in heavy precipitation. By introducing radiative transfer scheme in a mesoscale numerical weather model better physical relationship is seen between radiative quantities and cloud water or rain rates (Schomburg et al., 2012). Further, Rajeevan et al. (2010) have demonstrated sensitivity of microphysical schemes on thunderstorm occurred over southeast India. In another experiment for understanding mesoscale convective systems (MCSs), Done et al. (2004) have shown increased accuracy in prediction of convective system mode over Mid America Airport, Illinois, US by employing explicit scheme. Similar experiment with explicit convective parameterization within WRF framework has shown added values for high resolution forecast of convective system mode (Weisman et al., 2008). Studying two of the north-Alpine heavy precipitation events, Zangl (2007) has shown fact of proper representation of topography for explaining better small-scale precipitation variability. Over Indian Himalayan region, Das (2005) has demonstrated strength of mesoscale model for weather forecast.

In Indian meteorological parlance, though, particularly cloudburst events are frequently referred across in numerous researches, but are not well defined and lack in their assessment and understanding. These events are governed by much unknown complex convective and orographic processes. Hence, so far no set definition leading to cloudburst is provided. It is primarily linked to the high precipitation event over much localised area in very short time span. As per the IMD, cloudburst phenomenon characterized by high intensity precipitation, usually more than 100 mm/h, within a short span of time, over a small area. But then this definition remains to be very qualitative and associated dynamics and thermodynamics in correspondence with orographic interactions over the Indian Himalayas remain missing.

Keeping these facts in view present study attempts to provide understanding of physical and dynamical and other important processes associated with cloudburst events within following objectives.

## 2. Objectives

1. To study through extreme precipitation index to find out if the cloudbursts are captured over Indian Himalayas
2. To analyze large scale forcings causing the heavy precipitation associated with cloudbursts
3. To conceptualize the cause of and define cloudbursts as a localized precipitating event by describing the local forcings

## 3. Data and Methodology

### 3.1. Data used and referred in the present study

Local flash flood information are collected from Office of the Tahsildar, and I&FC, Leh (Ladhak), India. Various sources of cloudbursts reported within the southern rim of the Indian Himalayas are considered to compile the present review. Some of the sources are from print and public media (which at times only report the occurrence from societal point of view and do not have much research and science attached to it). Due to lack of the station observations over the data sparse Indian Himalayas, available global observational datasets have been utilized for the study. The observational datasets used in this study include:

1. National Aeronautics and Space Administration (NASA) Modern-Era Retrospective Analysis for Research and Applications (MERRA) (Rienecker et al., 2011) dataset with 6 hourly three-dimensional atmospheric analyses: Goddard Earth Observing System data assimilation System version 5 (GEOS-5) is used to generate this meteorological data assimilation product at a spatial resolution of 0.5° x 0.7°available from 1979 onwards. This dataset is downloaded from http://disc.sci.gsfc.nasa.gov/daac-bin/FTPSubset.pl?LOOKUPID_List=MAI3CPASM.
2. Version 7 Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) (Huffman et al., 2007) daily derived precipitation and 3 hourly rain rate data: TRMM multi-satellite precipitation analyses have a spatial resolution of 0.25° x 0.25° available from 1998 onwards. TRMM datasets focus on tropical region precipitation and thus have a horizontal coverage of 180°W – 180°E and 50°S – 50°N and is downloaded from ftp://disc2.nascom.nasa.gov/data/TRMM/Gridded/.
3. Climate prediction centre MORPHing (CMORPH) technique (Joyce et al., 2004) generated precipitation dataset: This provides global precipitation estimated from passive microwave and infrared satellite data available from 2002 onwards. CMORPH data is having 30 min temporal resolution and 8 km spatial resolution and daily precipitation estimates at 0.25° x 0.25° spatial resolution. This is the reprocessed data denoted CMORPH version 1.0 with gauge and satellite blended precipitation estimates and is downloaded from ftp://ftp.cpc.ncep.noaa.gov/precip/CMORPH_V1.0/CRT/ datasets are used in this.
4. Outgoing Longwave Radiation (OLR) data of the National Oceanic and Atmospheric Administration (NOAA) interpolated OLR (Liebmann and Smith, 1996): This global

dataset is available at 2.5° x 2.5° horizontal spatial resolution from 1974 onwards. This data is provided by Earth Systems Research Laboratory, NOAA, USA and is downloaded from http://www.esrl.noaa.gov/psd/data/gridded/data.interp_OLR.html.

5. Hourly observation precipitation records are taken from Self Recording RainGauge (SRRG) stations of India Meteorological Department, India.

### 3.2. Methodologies adopted by various researches to define cloudburst

In the Indian Himalayas, exact location and timing of cloudbursts are very elusive as being much localised convective events their occurrences are less monitored/observed. These events are reported due to their associated impacts of flash floods, damages etc. in the downstream basins. In addition, due to lack of station observations over data sparse Indian Himalayan region, at times corresponding analysis and understanding of cloudburst mechanism becomes challenging. At times local cloudbursts leading to flash flood information are collected at some of the local government offices. And some of the documentations and listings of these events are available from the other published works and literatures. Available cloudburst events are collected from various sources across the southern rim of the Indian Himalayas and are listed in Table 1. It provides details, damages and associated precipitation reported by various sources. Corresponding position of these cloudbursts are marked along with the Himalayan topography in Fig. 1. Most of the researches to understand their mechanism remained objective (Joshi and Maikhuri, 1997; Joshi, 2006; Juyal, 2010; Gupta et al., 2013). However in the recent decade, a few of the researches highlighted the associated dynamics by employing modelling framework (Das et al., 2006; Kumar et al., 2012; Thayyen et al., 2013; Kumar et al., 2014; Rasmussen and Houze, 2012; Shrestha et al., 2015). Using clustering technique, Pabreja (2012) has analysed Leh cloudburst event of 06 Aug 2010. Hobley et al. (2012) have provided reconstruction of this event using geomorphic signatures. They could demonstrate the intensity within the downstream basin in the Leh catchment. Chaudhuri et al. (2015) studied formation of a cloudburst based on analysis of observation and modelling efforts. In their work they studied back trajectory of the event as well. In the present study, five different cloudbursts, out of many described in Table 1, over the Indian Himalayas (Leh region) are studied based on observational and modelling strategies to arrive comprehensive definition of it.

## 4. Results and Discussion

In the present review authors tried to discuss findings on most of the important issues linked with cloudburst events right from precipitation details – dynamical forcing – orographic forcing – geomorphology – impact on society etc. in the following sections.

### 4.1. Cloudbursts and associated precipitation

The upper air flow pattern over the Indian sub-continent including the Himalayan region is governed mainly by the subtropical ridge and its movement with seasons. The continental effects, reflected in large annual and diurnal range of temperatures are more prominent towards west than the central or eastern part of Himalayas (Pangtey and Joshi, 1987).Towards the end of May the upper air circulation over the Himalayas undergoes a significant change. The sub-tropical high pressure ridge (STR) shifts northwards rather abruptly (at about the time of onset of the Indian summer monsoon (ISM) over the Indian subcontinent).

Based on 1961 – 1990 wind climatology, during April, pre-monsoon period, westerly flow dominates at 300hPa over the Indian subcontinent. Stronger core of westerly of the order of 60 knots remains over the eastern central India at and around 25$^{o}$N 90$^{o}$E, Fig. 2a. At further higher level of 100hPa, westerlies remain with an associated anticyclonic flow over the Indian Ocean, Fig. 2b. During July, monsoon period, at 300hPa and 200hPa levels, Fig. 2c, the STR lies between 27°N to 32°N. At 100hPa, Fig. 2d, it further moves northwards and lies over central parts of the Himalayan region (roughly at 32ºN) and the anticyclonic circulation covers the entire Himalayan belt. Easterly winds prevail to the south of the subtropical high. These easterlies increase in speed rapidly with height from 200hPa, reaching a maximum strength between 150hPa and 100hPa (IMD, 2003). With the withdrawal of the monsoon, the STR begins its southward movement and the upper air flow over the Himalayan region reverts to winter regime. As per records and literature most of the cloudbursts have been reported from Himalayan region during the southwest monsoon period (Jun - Sep).

A percentile analysis (99.9) of the hourly rain recorded in around 250 SRRG stations of IMD indicates the requirement of a change in the threshold of 100mm/h (as defined by IMD) to classify a cloudburst phenomena. The rare precipitation events in most of the stations along the foothills of Himalayas are between 70 - 80mm/h (Fig. 3a).The rain rate is also high in Gujarat and Rajasthan, but this could be explained as the data set used for the percentile analysis (hourly rain>0mm) varied across different regions .The annual average frequency of rain hours (No. of hours with rainfall >0mm) is greater than 900 hours (equivalent to 38 days of continuous rain) in sub-Himalayan Gangetic planes, Assam and Meghalaya and less than 100 hours (equivalent to 4 days of continuous rain) in extreme western parts of the country. The rain hours decrease, as we move from east to west across Indian region. The annual frequency of hourly rain rate intensities greater than 30mm is also highest in northeastern India and sub-Himalayan West Bengal followed by eastern India, Uttarakhand, Punjab, Himachal Pradesh and west coast of India. The area along the foothills of Himalayas has the highest (1%) contribution of high intensity (>30mm/h) rainfall events as compared to other regions, which also are showing high values of rain rate in Fig. 3a (Ray et al., 2016a). The instances of rain rate >70mm/h in SRRG stations during the period 1970 - 2010, over the Indian Himalayas (Uttarakhand, Himachal Pradesh and Jammu & Kashmir) is shown in Table 2. The analysis of hourly rainfall indicated only 3-4 instances of recorded rainfall > 100mm/h from 1970 - 2010. Most of the events occurred in the month of Jul and Aug and 80% of the instances occurred when the total accumulated precipitation on that day was less than 200mm and 10% of the events were a part of a larger synoptic scale driven systems (>200mm/day). The diurnal variation of rainfall for all the instances depicted in Table 1 is shown in Fig.3b and 3c .The events which had accumulated rainfall more than 200mm/day (black line) had multiple peaks, while other events had a single major peak of rain rate >70 mm/day and lower rain rates in the remaining hours. These instances were unable to include the cloudburst events reported by researchers, media and public (Table 1). The hourly rain rate in most of the events reported in Table1 is not known due to non availability of SRRG data but some of these events had reported accumulated rainfall more than 200mm/day. As suggested by Deoja et al. (1991) whenever the downpour ranges between 200-1000mm/day, intermittent 100 - 250mm precipitation in an hour can occur and thus can be termed as a cloudburst. Doppler weather radar (DWR) data in that region can further substantiate the claim (Ray et al., 2016b). The mismatch between Table 1 and Table 2 emphasizes the need for a cloudburst definition based on more inputs like damage potential and vulnerability to be considered along with the precipitation thresholds for defining a cloudburst event. Several places in the southern rim of the Himalayas are affected by cloudbursts go unreported, due to non availability of an observation or a weather station and/or undetected due to non availability of Doppler weather radar. Analysis of past data thus indicates that isolated occurrence of >70 mm/h precipitation may not cause as much damage, as that caused by continuous precipitation over a period of 24 - 48 hours, with intermittent hours of rain rate >70mm/h. Local people affected by cloudbursts have also reported normal rains for hours before and after a cloudburst event for many hours (Joshi and Maikhuri, 1997).

Most of the events are found to be reported during monsoon months and further confirming the fact that most of the isolated events of precipitation of >70mm/h during pre-monsoon months may not cause destruction amounting to cloudburst but a sustained precipitation >200mm in past 24 hours over a station with intermittent hourly rain >70mm may qualify to be a cloudburst. Thus it is time to reassess and revaluate the IMD definition of associated precipitation of cloudburst >100mm/h to either >100mm/15min. In addition, multiple cell of cloudburst needs to be negotiated within the event leading to spell precipitation.

### 4.2. Cloudbursts and associated precipitation observational analysis

To investigate associated dynamics of the cloudburst events, few of the cloudburst events as described in Table 1 are discussed comprehensively along with previous studies by other researcher. Out of these cloudburst events vigorous five events chosen are listed in Table 3 for further deliberation. Precipitation received during these cloudbursts are shown in Fig. 4 from TRMM, Fig. S1 from CMORPH daily 0.25° dataset and Fig. S2 from CMORPH 8km gridded observational dataset. From these daily gridded precipitation distributions, it is seen that cloudburst events 2, 3 and 5 show higher precipitation; whereas cloudburst events 1 and 4 show comparatively lesser precipitation. The observational datasets do not capture precipitation intensity associated with the corresponding cloudbursts in the range of 70-100 mm/h. However, CMORPH 8km dataset (Fig. S2) shows higher precipitation distribution than that from the corresponding CMORPH daily precipitation dataset (Fig. S1). Specifically, CMORPH 8km gridded dataset shows corresponding amount of precipitation associated with cloudburst event 5 which is not well represented in CMORPH daily precipitation dataset having lower resolution.

This can be attributed to better representation of orography in the higher resolution CMORPH datasets providing better representation of precipitation.

Selected five cloudburst events are simulated using the Advanced Research version of the Weather Research Forecast modelling framework (WRF- ARW 3.4.1, Skamarock et al. 2008; Wang et al. 2010). The model was configured with multiple nests (27km × 9km × 3km horizontal model resolutions) centered over Leh (34°09'N, 77°34'E) which was the locale with intense rainfall reports. The model was initialized using the 1 degree resolution NCEP Final Analysis (FNL) field. The microphysics and planetary boundary layer physics schemes used in the model configuration are WRF Single Moment six class cloud scheme and the Yonsei University Scheme (YSU) respectively as used in previous the Leh cloudburst studies (Ashrit 2010, Kumar et al. 2012, Thayyen et al. 2013). Kain Fritsch cumulus scheme (Kain 2004) is used for convection scheme with explicit run for the innermost domain of 3km. Due to brevity of volume, experimental details of the modelling design and precipitation analysis is presented in very brief here. For elaborated framework and discussions refer articles Chevuturi et al. (2015); Thayyen et al. (2013) etc. Three hourly TRMM rain rate based precipitation fields for cloudburst event 2 are presented in Fig. 5a, 5b and 5c for 05, 06 and 07 Jul 2005 respectively. It is seen from the figures that in the observed fields concentrated precipitation maxima zone during the cloudburst events are seen. While investigating these fields in the model simulations we don't find exact location of the precipitation maxima and at times we don't find at all the corresponding higher precipitation within the model environment as reported in these selected five events (since model could not capture precipitation fields in some of the corresponding simulations and hence data is not presented). However in observations, Fig. 5 and Fig. S3-S6, within the time slice cumulative precipitation shown sometimes does match with the corresponding cloudburst events outburst. Overall comparisons with the corresponding observations show that there are shifts in positioning and timing of the cloudburst precipitation maxima as reported by various sources at ground. This is one of the crucial limitations of the cloudburst events to get captured in the modelling fields. It is also pertinent to mention it here that in real time observations as well actual positioning and timing of the cloudburst is elusive. Further, significant gaps in the initial fields also might lead to poor performance in models in accurately representing the cloudbursts. This can be the cause and reason of why model misses some of the cloudburst events (temporally and/or spatially) but captures some events very accurately. For example, Leh cloudburst of 2010 was captured very well by the model (Thayyen et al., 2013) but other cloudburst events modelled in here were not. Thus, this remains an important scientific question to assess the cloudburst characterization within the modelling framework. To explain this critical threshold problem associated with cloudburst events, an attempt is made to look into and is explained in the succeeding sections.

Further, in all the gridded precipitation observational datasets temporal and spatial displacement in the peak maxima precipitation associated with the cloudburst occurrences is seen. These elusive peak precipitation maxima remains a challenge while studying the cloudbursts through numerical simulations as the observational datasets cannot be used to verify the model simulated output. Cloudbursts being a much localized phenomenon thus have a limited temporal and spatial extent. Thus, invariably it is as well not possible to capture the cloudburst events in the station observations. This issue is more pronounced in the Himalayas with highly variable orography which may not capture the cloudburst. As the station might be not having hourly precipitation readings and/or precipitation might completely miss the station and occur in the neighbouring region. With this lack of the station data even the observational gridded datasets might not capture the event. Though, satellite information might provide indicators of the precipitation events, which are converted into precipitation output. But this satellite information might underestimate the precipitation scaling of these sporadic events.

### 4.3. Cloudbursts and large scale forcings

The large scale forcing in terms of geopotential height at 700, 500 and 200 hPa associated with cloudburst events listed in Table 3 is shown in Fig. 6. Figures show a common feature of low pressure in the lower troposphere, 700 hPa, developing over the northern Indian region associated with a cyclonic circulation in all the cloudburst events. This anomalous circulation pattern is mainly associated with the monsoonal flow. Similar circulation pattern was also reported by Chevuturi et al. (2015). This large scale convective forcing may attribute to the enhancement of the localized cloudburst events. But it is to be noted that this anomalous cyclonic circulation is over the central and western region of the India rather than over the region where the cloudburst occurred. It is as well important to note reduced impact of the mid-latitude circulation pattern called the western disturbances (WDs, Dimri et al., 2015). Only in case of cloudburst event 2, an active WD in the mid- (500 hPa) and upper (200 hPa) level is seen as a trough embedded in the sub-tropical westerly jet (SWJ). This mid- and upper- level trough associated with the WD shows an interaction with the lower level cyclonic circulation to form a combined system. This is a direct consequence of large scale interaction and associated forcing leading to a cloudburst event. Other than the cloudburst event 2, other cloudbursts show a lower pressure region developed in the upper tropospheric region. The anomalous WD interacting with the cyclonic circulation associated with the monsoon may bring break conditions in the monsoon which is associated with higher precipitation incursion over the Himalayas. Other than the cloudburst 2, rest of the cloudbursts show a low pressure over the northern Indian region in relation with the SWJ placed above. Yatagai et al. (2012) suggested that the cloudbursts over the Himalayan region are a result of wave energy transport of the jet stream above the region. The wave like motion of the jet stream is clearly visible in the 200 hPa circulation of all the cloudbursts in the Fig. 6. The wave like motion of jet stream results in energy transport from the Caspian Sea towards the north of India. This might be one of the large scale forcings influencing cloudbursts but it is not clear how much it directly impacts the cloudbursts. There are few of the researches highlighting the role of large-scale forcings leading to synoptic scale extreme events leading to flooding in and along the Himalayas, but not linking to mesoscale cloudburst event. Houze Jr et al. (2011) provided comprehensive explanation for summer 2010 Pakistan flood due to anomalous atmospheric conditions. In this event of catastrophic runoff and flooding rainstorms were displaced to the west over the arid and mountainous region. In such event anomalous propagation of Bay of Bengal depression and its moist environment across the sub-continent to the Arabian Sea together with the development of high pressure over the Tibetan Plateau favoured the moisture channel towards the mountain barrier. Webster et al. (2010) have shown the possibility of prediction of such events and associated large scale flow patterns leading to moisture flow over the Pakistan region using weather forecast models. However, predicting exact form of the cloudburst remained elusive. Investigating same event, Lau and Kim (2012) proposed the physical connection of two extreme events i.e., Russian heat wave and Pakistan flood. Hong et al. (2011) have illustrated role of European blocking and mid-latitude interactions leading to early propagation of moisture influx over Pakistan due to Bay of Bengal depression. In similar but another event of heavy deluge over the Uttarakhand, Joseph et al. (2015), proposed the ability of extended range prediction, showing interaction of mid-latitude westerly trough with monsoon depression leading for heavy precipitation. According to

Chevuturi and Dimri, 2016, merging of WD with monsoon trough acts as a pulsatory extension of monsoon (PEM) over the Uttarakhand Himalayas. Due to this merging an occluded discontinuity forms over the steep Himalayan orography. This discontinuity forms from the cold gradient of the frontal WD in upper troposphere (leading section warmer and trailing section colder) and warmer and more humid monsoon flow in lower troposphere.

OLR is analyzed using NOAA dataset (Fig. 7). Though precipitation analysis and large scale circulation patterns could not able to capture exact indicators of all cloudbursts, say, over the Leh region (specifically cloudburst 1 and 4). But when the OLR data is analyzed, we see lower OLR values observed over the regions in all the cloudburst events. Evolution of these events indicates the clouding developing over the region. According to Das et al. (2006) *"cloudbursts in India occur when monsoon clouds associated with low-pressure area travel northward from the Bay of Bengal across the Ganges plains onto the Himalayas and 'burst' in heavy downpours"*. The cloudburst 6 is primarily got moisture incursion from Bay of Bengal.

But on analysing vertical integrated moisture flux and transport for Leh cloudbursts 1-5, Fig. 8, it is seen that the moisture flow is mainly from the Arabian Sea. Even in case of cloudburst event over Okhimath, the source of moisture is from the Arabian Sea (Shrestha et al., 2015). Yatagai et al. (2012) as well shown that during cloudburst event 5 over Leh, south-easterly flow prevailed which converged the moisture towards and over the Leh region. Rasmussen and House Jr. (2012) comprehensively provided understanding on large scale forcing associated with Leh cloudburst of 4 – 6 Aug 2010. A conceptual model is illustrated demonstrating integrated role of important meteorological element which led to this anomalous event. Low level moisture convergence in southern side of the Himalayas and convective cells in northward of the Himalayas over Tibetan plateau led to such event.

With these analyses it can be concluded that there might be indicators for the development of cloudbursts within large scale forcings. But as seen there is not always a direct impact of the large scale forcings on the event. This is because, as stated before, that the cloudburst is a much localized event. But if the trigger of such events is not captured in observational or initial and boundary conditions, these will not be accurately simulated or captured in the model simulations at well (which is further discussed later). This is one of the possible reasons for the failure of the models in capturing the cloudburst events. Chaudhuri et al. (2015) showed importance of the presence of the sufficient amount of moisture for the formation of conditions leading to cloudburst. During the study period, a monsoon trough was present over the Indian mainland, which led the moisture from neighbouring Arabian Sea and Bay of Bengal into the Himalayan region.

### 4.4. Cloudbursts and Orographic Forcings

Large scale orographic interactions are proposed by various authors. Barros et al. (2004) have illustrated use of remote sensing information to provide linkages between space-time variability of cloud, precipitation, large scale circulation patterns and topography. It demonstrated the spatial scale forcing ranging from few km to continental scale and time scale for onset and intraseasonal variability of ISM. Romatschke and Houze Jr. (2011) have shown that along the western Himalayan region precipitation is associated with smaller but highly convective systems. Chiao et al. (2004) while studying over Alps have illustrated importance of dynamical forcing associated with the upslope-induced and near-surface horizontal velocity convergence – induced vertical motion leading to upslope motion with heavy precipitation concentrated over the mountain peaks. Chen et al. (2007) have illustrated role of Tibetan complex terrain in dynamic blocking which enhances stronger water vapour convergence in northwest Sichuan region and thus intensifying the local severe storm. While studying role of terrain and landcover on convective systems during ISM, Medina et al. (2010) have shown different interactions over western and eastern Himalayas.

To understand the localized nature of these cloudburst events vertical distribution of some of the important variables along the orographic details are studied. Barros et al. (2004) have provided a schematic framework to define organised formation of leading-line-trailing stratiform mutli convective system (MCS) type structure and this figure is reproduced as Fig. 9. It shows that not only elevation, but especially the spatial arrangement of topographic gradients determine precipitation forming mechanism and associated precipitation. To understand topographic forcings better, modelling based assessment associated with the selected cloudburst events is carried out and is presented in the Fig. 10 – 13. As from the above analysis we can note that the large scale forcing usually may not have a very significant impact on the cloudburst phenomenon. So consequently it can be assumed that the cloudbursts must be a result of localized forcings and orographic interactions within the Himalayan ranges. In this sub-section localized forcings and orographic related interactions leading to the cloudburst events are discussed. Thus hypothesis for the cloudburst formation due to localized forcings over mountainous region includes interactions of convective triggering and orographic locking. The lift of a moist air parcel that is initialized by a convective trigger is enhanced along the steep orography. The rapid lifting due to combination of convection and orography results in orographic locking of convectively triggered cell in swift cloud formation which precipitates suddenly causing cloudburst.

Fig. 10 (Fig. S7) shows the vertical distribution of the omega (vertical pressure velocity) and specific humidity along 35.15$^{o}$N latitudinal (77.57$^{o}$E longitudinal) cross section at Leh. Here we observe increasing negative omega along the increasing orography of the mountains of Ladhak region and over Leh. This negative omega represents rising vertical pressure velocity indicating rising motion over the region. Such a negative omega over the Leh region is indicative of the rapid lifting as mentioned in the hypothesis above. Further, the higher specific humidity values over the Ladhak region represent the moisture presence. The moisture over the region is due to incursion from mainly the Arabian Sea that was discussed in the previous sub-section. Increased moisture over the region provides the buoyancy to the air which is conducive for lifting conditions. Thus, for cloudburst events within the Himalayas ranges (Leh), there is vertical rising of the moist air parcels (Chevuturi et al., 2015, Shrestha et al., 2015). There was vertical rising motion as there was low level convergence and upper level divergence at a localized level causing the rapid lifting of the moisture.

These observations of lifting of moisture laden air are also represented in Fig. 11 (Fig. S8) based on vertical distribution of perturbation of equivalent potential temperature (EPT) and vertical moisture flux along 34.15$^{o}$N latitudinal (77.57$^{o}$E longitudinal) cross section at Leh. Here the vertical moisture flux shows negative values along the orography and particularly over the Leh region which is indicative of the lifting motion of moist air. It illustrates that as and when moist air moves along the uphill direction, it sheds along the path and mainly limits within the adjacent lower pressure height in the orographic flow. Figures also represent the vertical distribution of the perturbation of the EPT. For the calculation of this perturbation of EPT, EPT of each grid point is subtracted by the area average of the whole domain at each pressure level. The regions of positive perturbations of EPT represent higher temperature and moisture content. These regions correspond to the regions of instability and can be considered as the cause of the thermodynamically induced storms. EPT is a variable that we are using to indicate the convective trigger of the cloudbursts. The cloudburst event 1 shows a slow increase in the positive EPT along the orography of the region. Cloudburst events 2 - 5 show higher positive EPT values over Leh and along the orography of the region. Similar high values of EPT were also seen over Ukhimath in model simulated output during the cloudburst event (Chevuturi et al., 2015). The peak of EPT perturbation indicates the sharp increase of instability or potential energy, which is required for the convective cell development. The reduction in the perturbation of EPT results in the decrease of instability. Tompkins (2001) described a similar development of EPT in deep localized convective storms. Orographic precipitation also shows increased EPT as described by Chiao et al. (2004). With a clear increase in the EPT along the slope of Himalayas, it can be concluded that convective storms get subsequently locked by the orography.

To investigate it further, Fig. 12 (Fig. S9) shows the vertical distribution of hydrometeor mixing ratios with cloud liquid and cloud ice mixing ratios along $34.15^{\circ}$N latitudinal ($77.57^{\circ}$E longitudinal) cross section at Leh. The increase in these mixing ratios is indicative of cloud formation over the region. As observed in the figures there is an increase in cloud hydrometeors mixing ratios over Leh except in cloudburst event 1. Cloudburst event 1 shows formation of the hydrometeors but these are displaced and the values of mixing ratios are lower. Though cloud formation was observed over Leh as an indication of lower OLR values discussed before. These increased mixing ratios of hydrometeors were also discussed by Das et al. (2006). Das et al. (2006) indicated the formation of the hydrometeors as a result of rapid uplifting of the warm and moist air parcel.

Further, to connect with Fig. 9 (Barros et al., 2004), Fig. 13(a) illustrates spatial distribution of model simulated reflectivity associated with cloudburst event of 13 Sep 2012 18UTC simulated using WRF modelling framework with explicit convection scheme (Chevuturi et al., 2015). Associated precipitation cloud formations along the valley-ridge cascading formations are attributed to the presence of hydrometeors in the atmosphere with increased reflectivity values. Higher precipitation maxima associated with reflectivity values up to 40 dBZ are well in comparison with the observed DWR reflectivity in Fig. 1b of Chevuturi et al. (2015). Detailed analysis of combined hydrometeor (cloud water, cloud ice, rain water, snow and graupel) mixing ratios and reflectivity at the location of maximum reflectively is shown in Fig. 13b and 13c respectively. It is apt to mention it here that combined hydrometeor mixing ratios provide signature of the cloud formation in the vertical and reflectivity represents the precipitation reflectivity. Thus, from these later two figures it is seen that the cloud formation reached up to 250 hPa to form high cloud tops. Such clouds can be the cumulonimbus (thunderstorm) clouds that are said to be associated with cloudbursts according to Upadhyay (1995).

While simulating the same event using Consortium of Small-scale modelling (COSMO) (Doms and Schaettler, 2002; Steppeler et al., 2003; Baldauf et al. 2011) framework, Shrestha et al. (2015) have shown very interesting results. Fig. 14 represents the capture of positioning and timing of locale cloudburst event maxima precipitation. This exact identification of position and time of cloudburst event gives a confident picture based on modelling effort. To further understand the associated mechanisms behind the extreme precipitation, model based daily accumulated precipitation over the area along the topography is presented in Fig. 14a. Regional position is located along the protruding foothills of the Himalayas with adjacent dissected valleys on either side, which open up towards the southwest. The simulated maximum daily accumulated precipitation is of the order of over 200 mm/d, Fig. 14b. Here it is interesting to note that in a very short time span precipitation amount peaks. Corresponding meteorological conditions and the potential mechanism behind this extreme precipitation led vertical hydrometeor qg values from 5 to 13 km with peak mixing ratios of 3.5 g/kg around 6 km (Fig. 14c). Transportation of cloud and rain drops reaches up to 11 km due to strong updraft in the glaciations regime where they exist as super-cooled drops. Due to glaciations regime interactions snow and ice particles extend from 6 to 14 km, with qs peaking nearly to 1 g/kg at 10.5 km and qi peaking to 0.5 g/kg at 13 km height. In glaciations regime graupel-dominated microphysical process takes place on two accounts in model physics: (1) primarily due to riming of snow and freezing of raindrops or (2) due to freezing of raindrops by collision with ice particles. Below the melting level, due to the melting of graupel enough moisture becomes available in the vertical column, and hence intensification of raindrop formation. At this time, a second shallow convective system develops over the ridge line, which also propagates eastwards and eventually dissipates along with the deep convective storm later.

### 4.5. Cloudbursts and its understanding with modelling

There are few researches made to understand dynamical and thermodynamical processes associated with different cloudburst events, apart from the above discussed. Das et al. (2006) studied Shillagarh cloudburst event of 16 Jul 2003 by employing Mesoscale Model 5 version 3.6 (MM5) framework. By configuring it in multiple nested domains with attention to horizontal resolution and cloud microphysics parameterization, a conceptual model for cloudburst event is proposed comprising of development of vertical shear, vertical motion and moisture distribution within its lifecycle. Chevuturi et al. (2015), while simulating 13 – 14 Sep 2012 Ukhimath cloudburst event using WRF model version 3.4.1 with Advance Research WRF dynamical solver (Wang et al., 2010; Skamarock et al., 2008) illustrated role of steep orographic forcings in rapid dynamical lifting with increased convergence of moist air at lower level along the foothill of the mountain and rise along the orography to form the updraft zone of the storm. Simulating the same event using COSMO framework (Doms and Schaettler, 2002; Steppeler et al., 2003; Baldauf et al. 2011), Shrestha et al. (2015) have shown three step mechanism associated with the cloudburst event. Kumar et al. (2014) using National Aeronautical and Space Administration (NASA) Unified Weather Research and Forecasting Model (NU-WRF) simulated Leh cloudburst leading to flash flood in the steep edge of the Himalayas. Using coupled land surface and atmosphere model, Kumar et al. (2014) illustrated model storm trailing as a travelling mesoscale squall line with leading convective line trailing stratiform region, and mid-level inflow jet. By employing nested WRF modelling experiment, Thayyen et al. (2012) have established run off associated with Leh cloudburst event 4 - 6 Aug 2010. Sensitivity experiment by using different cloud microphysics parameterization schemes within nested WRF framework while simulated the same Leh cloudburst event, Kumar et al. (2012) have illustrated closer positioning of model precipitation near to the observation. To critically evaluate the cloudburst based on satellite monitoring of precipitation, Mishra and Srinivasan (2013) have proposed a mathematical framework to compare the precipitation during the Kedarnath cloudburst event of 16 – 17 Jun 2013. They suggested that rain index based technique is efficient to study heavy precipitation events at finer scale over the Indian Himalaya region. Integrating clustering technique with the numerical weather prediction model outputs, signal formation of cloudburst events can be assessed and used with short lead time for prediction purposes (Pabreja, 2012). Chaudhuri et al. (2015) have provided comprehensive details based on one of the cloudburst study using four nest WRF model and corresponding observations. Using best combinations of parameterization schemes best reproduction of the observed diurnal characteristic associated with the cloudburst event is explained. And, stressed the need of assimilating the high resolution measurements within the modelling framework.

### 4.6. Cloudbursts and geomorphology

The lack of ubiquitous local weather stations coverage in the Himalayas causes limitation in quantifying the extreme precipitation vs gradation process, which is vaguely recognized as cloudburst. In the Himalayan terrain, the burst is invariably observed and experienced in the form of flash flood and sudden debris flow accompanied by heavy precipitation. Often, it is the adverse interaction of society, in the form of loss of life and habitat, with the heavy precipitation resulting flash flood and debris flow (Table 1) bring notice to the occurrence of cloudburst and therefore the short term heavy precipitation in uninhabited region remains a gap in the understanding of this natural processes.

It is observed that the bulk of the cloudburst related gradational phenomenon in the western Himalayas are observed between 1000 - 2500 m topographic range to the south of the Greater Himalayas having ~5000 m height above mean sea level (Fig. 15). Though there are some notable exceptions in recent past when the region >3000 m average height reported cloudburst viz., in case of 6 Aug 2010 Leh cloudburst in the cold desert of Ladakh (Juyal, 2010; Hobley et al., 2012); unconfirmed and debated 2013 cloudburst over the Uttarakhand region in Garhwal Himalaya (Mishra & Srinivasan, 2013), etc. The attempt has been made to characterize cloudburst occurrence with the direction of the catchment slope (Asthana and Asthana, 2014). To generalize the geomorphology we choose three catchments, which experienced cloud burst in recent past, from varying height range, size and directions (Fig. 15a) in the upper Ganga catchment to understand the role of local topography and drainage pattern.

The Asi Ganga catchment, drained by rivers Asi Ganga and Kaldi gad, with >25 km long trunk stream flowing between ~3400 - 1200 m at an average gradient of ~90 m/km (Fig. 15a) experienced a cloudburst on 3 Aug 2012 causing flash flood, debris flow and extensive toe erosion towards lower reaches of the catchment. The slope distribution in the catchment shows higher slopes towards upper catchment along the northeast to southwest trending Kaldi gad and the gentler slope towards lower reaches (Fig. 15b) along the north to south trending Asi Ganga with decreased gradient of <50 m/km. The extensive mass wasting due to enhanced runoff during the cloudburst (Gupta et al., 2013) was observed as the bed load and runoff converged from across the catchment along this less rugged zone (Fig. 15b). The pre- and post- cloudburst comparison of satellite imagery clearly shows the extent of debris flow and slope failure along the lower reaches of the Asi Ganga (Fig. 15b). The enhanced discharge at the catchment outlet increases the height of water column of the flash flood and affected a wider area of the slope causing damage to life and property as reported during the event (Gupta et al., 2013). It is important to note that the slope became unstable at the junction of high gradient Kaldi Gad with the Asi Ganga and contributed extensively to the debris and sediment load to the gentler north to south trending stream outlet (Fig. 15b). This characteristic knee bend turn of trunk stream with increasing gradient and closed topography is commonly observed along other catchments affected by cloudbursts in the region. Another smaller catchment along the Bhilangana river, which is frequently affected by cloudburst and associated mass wasting, lies between 800-1800 m, is drained by >5 km long seasonal stream having closed valley with high slope (Fig. 15a and 15c). The trunk stream has >160 m/km average gradient knee bend turn near the catchment outlet where several levels of debris fan are preserved. This knee bend stream turn appears like landslide zone on the imagery but the field observation shows the zone is stable, rocky and steep