Review

A review of atmospheric and land surface processes with emphasis on flood generation in the Southern Himalayan rivers

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Article history:
Received 9 January 2016
Received in revised form 29 February 2016
Accepted 29 February 2016

HIGHLIGHTS

• Floods in the southern rim of the Indian Himalayas are a major cause of loss of life, property, crops, infrastructure, etc.
• In the recent decade extreme precipitation events have led to numerous flash floods in and around the Himalayan region. Sporadic case-based studies have tried to explain the mechanisms causing the floods.
• However, in some of the cases, the causative mechanisms have been elusive.
• The present study provides an overview of mechanisms that lead to floods in and around the southern rim of the Indian Himalayas.

ABSTRACT

Floods in the southern rim of the Indian Himalayas are a major cause of loss of life, property, crops, infrastructure, etc. They have long term socio-economic impacts on the habitat living along/across the Himalayas. In the recent decade extreme precipitation events have led to numerous flash floods in and around the Himalayan region. Sporadic case-based studies have tried to explain the mechanisms causing the floods. However, in some of the cases, the causative mechanisms have been elusive. Various types of flood events have been debated at different spatial and temporal scales. The present study provides an overview of mechanisms that lead to floods in and around the southern rim of the Indian Himalayas. Atmospheric processes, landuse interaction, and glacier-related outbreaks are considered in the overview.

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Keywords:
Himalayas
Flood
Glacial lake outburst
Cloudburst
Lake dam outburst
Precipitation

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http://dx.doi.org/10.1016/j.scitotenv.2016.02.206
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1. Introduction

Five major flood events in the Himalayan region from Pakistan to Assam in the past 10 years have occurred, highlighting the increasing prevalence of floods, inadequacy of infrastructure to combat floods, incomplete understanding of flood forecasting mechanisms, and the lack of preparedness in the region. Managing the Himalayan floods is a challenging task, since the floods result from a combination of atmospheric and land surface processes. The 2010 July–August flood in Pakistan is considered to be the worst ever flood in the region caused by the mesoscale convective systems (Houze et al., 2011; Webster et al., 2011; Lau and Kim, 2012). This was followed by the Ladakh flood in August 2010, which was caused by multiple cloudbursts in a span of three days generated by the passing low pressure system (Rasmussen and Houze, 2012; Kumar et al., 2014; Thayyen et al., 2013). In 2012, the Brahmaputra flood was also generated by torrential rains over steep mountain slopes. In June 2013, the Kedarnath floods were caused by high intensity torrential rains coupled with Chorabari lake outburst (Dobhal et al., 2013). The Kashmir flood in September 2014 was caused by an unusual convergence of monsoon and westerly winds, whereas the 2015 Zanskar flood was caused by a Landslide Lake Outburst (LDOF) (http://www.nrsc.gov.in/Phutkal.html). Apart from these major flood events, many local floods were recorded across the Himalayas in the recent past as listed in Table 1. These recent flood events highlight the need for a better framework for flood hazard mitigation and disaster risk reduction in the region.

Geographically and geomorphologically, the Himalayas have a unique positioning, located along the Karakorum in the west to Assam in the east (Fig. 1a), blocking the monsoon and trade winds from the tropics in summer and from extratropics in winter. Within the Himalayas, climate and hydrology vary at the regional to sub-regional scale. The climate of western Himalayas is mainly driven by wintertime weather (Dimri et al., 2015; Yadav et al., 2013), the climate of central Himalayas is driven by summer and winter monsoon (Shrestha et al., 1999), and the climate of eastern Himalayas is dominated by summer monsoon (Jhajharia and Singh, 2011). The lifting of monsoon moisture along the steep southern slopes of the Himalayas is a major driver of floods in the region (Fig. 1b). The principal non-monsoon flood regime of the Himalayas lies in the north-west of the monsoon regime, where major floods are also caused by glaciers and landslide damming. The high altitude glacier regimes are also the potential zones of non-monsoon floods, such as Glacial Lake Outburst Floods (GLOF). Hence, floods in the region have multiple geneses, offering a formidable challenge to flood management.

Our understanding of atmospheric and land surface processes that dictate flood characteristics in the Himalayan region have many gaps. This can be attributed to the complex geography and topographic interactions with large scale atmospheric flows and data gap/sharing issues. Conditions and physical processes that produce floods in the Himalayan region can be highly complex, comprising multiple geneses that often involve coupled and dynamic atmospheric and land surface processes (Barros et al., 2004; Dimri and Niyogi, 2012; Bookhagen and Burbank, 2006). Feedbacks between atmospheric, topographical, and geomorphological attributes may result in highly variable patterns and outcomes of water and sediment distribution in high altitude areas, including foothill and plain regions. Incomplete understanding of these processes often hinder effective flood management practices, especially flood forecasting.

### Table 1

<table>
<thead>
<tr>
<th>Number corresponding to Fig. 1</th>
<th>Flood event</th>
<th>Date</th>
<th>Dominant forcings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Pakistan, Indus River</td>
<td>Jun 2005</td>
<td>Landslide lake outburst</td>
<td></td>
</tr>
<tr>
<td>2 Nepal, Kosi River</td>
<td>Aug 2008</td>
<td>Breach in the Kosi embankment</td>
<td></td>
</tr>
<tr>
<td>3 Myanmar</td>
<td>May 2008</td>
<td>Tropical cyclone - Nargis?</td>
<td></td>
</tr>
<tr>
<td>4 Pakistan, Indus River</td>
<td>Late Jul and early Aug 2010</td>
<td>European blocking and tropical-extratropical interaction</td>
<td></td>
</tr>
<tr>
<td>5 Ladakh</td>
<td>Aug 2012</td>
<td>Cloudburst</td>
<td></td>
</tr>
<tr>
<td>6 Zanskar, Ladakh</td>
<td>Aug 2015</td>
<td>Landslide Dam Outburst</td>
<td></td>
</tr>
<tr>
<td>7 Pokhara, Nepal</td>
<td>May 2012</td>
<td>Landslide + glacier melt + ???</td>
<td></td>
</tr>
<tr>
<td>8 Kashmir</td>
<td>Jun 2013</td>
<td>Westerly-ISM monsoon + lake outburst</td>
<td></td>
</tr>
<tr>
<td>9 Assam, India Brahmaputra River</td>
<td>Sep 2014</td>
<td>Torrential Rain??</td>
<td></td>
</tr>
<tr>
<td>10 Assi Ganga, India</td>
<td>2012</td>
<td>Torrential rain</td>
<td></td>
</tr>
<tr>
<td>11 Rudraprayag, India</td>
<td>2005</td>
<td>Cloudburst</td>
<td></td>
</tr>
<tr>
<td>12 Ukhimath, India</td>
<td>2006</td>
<td>Cloudburst</td>
<td></td>
</tr>
<tr>
<td>13 Chenab, India</td>
<td>2008</td>
<td>Cloudburst</td>
<td></td>
</tr>
</tbody>
</table>
The objectives of this paper therefore are to: 1) review the dominant atmospheric and land surface processes that contribute to flood generation in the Himalayan region, drawing upon the reported flood events; and 2) discuss challenges and pathways to overcome adversities related to predicting, monitoring, and preparing for disastrous flood events.

2. Predominant atmospheric processes in Himalayan flood generation

2.1. Overview of precipitation mechanisms in the Himalayas

The Indian Summer Monsoon (ISM) provides a major part of annual precipitation for the Indian sub-continent during summer (June, July, August, and September: JJAS). ISM is an intriguing synoptic-scale phenomenon controlled by varying drivers (Annamalai et al., 2007; KrishnaKumar et al., 1999; KrishnaKumar et al., 2006; Turner and Slingo, 2011; Saha et al., 2012). The Tibetan High plays a significant role in defining the strength of ISM (Yasunari et al., 1991; Wu and Qian, 2003). This high pressure region blocks the northward propagation of the monsoonal flow. Many studies have defined varying durations of dominant monsoon spells or intraseasonal modes at 10–20 days and 30–60 days time scales for ISM (Hartmann and Michelsen, 1989; Goswami and Ajaya Mohan, 2001; Hoyos and Webster, 2007). Monsoons usually advance into the eastern Himalayan region by the first week of June, steadily progresses westward and cover most of the Himalayas by July 15. The influx of moisture to the eastern Himalayas is sourced from the Bay of Bengal, while the moisture into the western Himalayas is appended by the Arabian Sea as well. During the intermittent lull in the monsoon activity over the core monsoon region known as monsoon break period, the monsoon activities along the foothill of the Himalayas is intensified (Maharana and Dimri, 2015). In this case also, the Himalayan topography plays a dominant role in
defining the advancement of quasi-intertropical convergence zone (ITCZ) associated with ISM.

During the post-monsoon months of October and November (ON), the northeast monsoons (NEM) dominate over the Indian subcontinent and provide precipitation over the southeastern coast of the Indian peninsula. During NEM, the summer to winter circulation changes gradually, reversing wind patterns from southwest to northeast (Kripalani and Kumar, 2004; Kumar et al., 2007; Yadav et al., 2007). However, these winds have little influence over most of the Himalayas. In winter (December, January, February: DJF), the Indian winter monsoons (IWM) dominate and bring through western disturbances embedded within large-scale subtropical westerlies and precipitate in the form of snow over mountainous regions (Dimri et al., 2015). The interannual and intraseasonal variability associated with IWM has been a subject of various studies (Laat and Lelieveld, 2002; Dimri, 2013a, 2013b; Yadav et al., 2013). During DJF the spatial distribution of precipitation over central and western Indian Himalayas is strongly influenced by the interplay of western disturbances with the orographic barrier of the Himalayas (Dimri, 2004; Dimri and Niyogi, 2012).

Extreme rainfall associated with flashfloods occurring over the Himalayas is an outcome of various complex, non-linear interactive processes. At times, the interactive orographic forcing invigorates flash floods in tandem with atmospheric flows. Adhikari et al. (2010) have provided a Global Flood Inventory (GFI) which suggests that the majority of flood events (64%) are associated with short duration heavy rains, followed by events due to torrential rains (11%) during the monsoon period. These latter heavy rain events are particularly associated with localized causes, such as cloudbursts, lake bursts, landslides, and orographic forcings, etc. These events are distinctly different from the large scale monsoonal flow. The explicit differences in floods associated with large and localized flows are discussed in what follows.

2.2. Orographic forcing

Orographic interaction with large scale atmospheric flow and localized events determines the amplitude of rainfall over the Himalayan region. At times this higher amplitude rainfall is one of the leading causes of flood initiation. Examples of orographic control of the mountains aiding heavy rainfall are available for various mountain ranges across the world. Over the Andes basin, the interaction of Andean mountain front increases the moisture flux to rise along it (Bookeyhagen and Strecker, 2008; Romatschke and Houze, 2011). Such pronounced interaction of Andean mountain and the South American low level jet, associated with the South American monsoon, enhances precipitation (Boers et al., 2014). Based on a composite analysis of geopotential height and wind fields, Boers et al. (2014) showed northward propagating frontal systems and the associated anomalies to be the driver of extreme rainfall. In the United States, Colorado suffered from severe flooding in September 2013 due to the orographic interaction of Colorado Front Range with North American monsoon (Kim et al., 2014). Later, an unusual near-stationary low-pressure system led to a strong plume tropical moisture influx from the Pacific Ocean near Mexico towards the Colorado Front Range.

In the case of the Indian Himalayas, steep topography and land use heterogeneity plays a crucial interactive role in defining the weather and associated precipitation mechanisms. The latitudinal and longitudinal cross sectional distribution of the topography along and across the Himalayas highlights how the two-step topography determines the orographic forcing (Fig. 2a). Topographic variations along latitudinal and longitudinal cross sections induce different precipitation forming mechanisms leading to the associated precipitation amplitude. The corresponding latitudinal and longitudinal cross-sectional topography across the western Himalayas at 30°N, 35°N, 40°N, 70°E, 75°E, and 80°E is shown in Fig. 2a(1–3) and Fig. 2a(4–6), respectively, represents strong topographic gradients across the east – west and north – south directions. Such a distribution of topography also influences the regional precipitation. The winter (DJF) precipitation investigated in many experimental studies illustrates that in general precipitation peaks at and around ~4000 m and then decays even if topography increases (Fig. 2b) (Dimri and Niyogi, 2012). This suggests that in general precipitation is limited up to ~4000 m elevation in the Himalayan region. Associated physical processes limiting the precipitation are mainly due to the shedding of mass of saturated water vapor on the upslope side.

For analyzing the role of topography and/or orographic forcings, the latitudinal and longitudinal cross-sectional distributions of mean seasonal winter (DJF) precipitation simulated under two sets of modeling experiments as control (CONT) and subgrid (SUB) and the corresponding observed (CRU and APHRODITE) precipitation are depicted in Fig. 2b. To project the interactive role of topography, these distributions are also presented with the cross sectional topographies from model simulation (CONT and SUB) and observations (GTOP030 10 min). Interactive and topographic feedback or dependence of precipitation on the topography is evident in the spatial variability of precipitation amount across the Himalayas. In the cross sectional distribution of precipitation for model simulations have elevations similar to the observations. The corresponding precipitation distribution maxima and minima along the topographic elevation in the model field and observations are seen. Beyond ~4000 m elevation, reduced precipitation is seen in both the experiments and the observations. The temperature decrease along the mountain upslope with elevation increase and the resistance to the upslope flow results in cloud and precipitation formation. This rise of air sheds the condensed moisture along the upslope (Yasunari, 1976; Singh et al., 1995). This precipitation mechanism under the orographic influence leads to complex interactions. In the case of model, higher precipitation at high elevation points and less precipitation at low valley points than the corresponding observations are seen. In addition, model-simulated precipitation peaks are seen as in the corresponding observations with certain lead/lag in precipitation maxima at a few places. These differences in the values of SUB and CONT model fields are due to land surface and topography interactions as seen in the SUB experiment which uses finer topography than that in the CONT experiment (Dimri and Niyogi, 2012). The longitudinal cross-sectional topography is more variable than the latitudinal topography, particularly over the western Himalayas. Such aspects warrant further studies to understand the associated precipitation mechanisms and the interactive influence thereof.

2.3. Convection – Orography dynamics

Cloudbursts in and around the foothills of the Himalayas are typical convectively initiated orographically locked phenomena that subsequently lead to flashfloods (Thayyen et al., 2013; Rasmussen and Houze, 2012; Kumar et al., 2014; Shrestha et al., 2015). Many local flood events recorded across the Himalayas in the recent past were mostly generated by the cloudburst events. Localized events over Asiganga (Gupta et al., 2013), Rudraprayag, Ukhimath (Shrestha et al., 2015; Chevuturi et al., 2015), and Leh (Thayyen et al., 2013) are some of the examples from the recent decade. In the case of the Leh (Ladakh) flood (4–6 August 2010), a cloudburst was the dominant atmospheric phenomenon, leading to flash flooding and subsequent debris flow (Thayyen et al., 2013; Rasmussen and Houze, 2011; Kumar et al., 2014; Hoby et al., 2012). On 5 August 2010, a cloudburst had produced a lethal flash flood in the Leh town situated in the high arid Indus valley in northwest India. The rare penetration of monsoon into an otherwise non-monsoon area makes it difficult to predict and even more complex to understand it. During this particular time of ISM, the 500 hPa winds over the Leh region are normally westerly. However, preceding 03 days of the Leh flood, the 500 hPa geopotential height had shown an easterly jet, which remained persistent for those days. This quasi-stationary jet had led the mesoscale convective systems to move towards and over the Leh region. Simultaneously, there was a mid-
Fig. 2. (a) Map of western Himalayan latitudinal cross sectional topography ($10^2$ m) corresponding to the CONT experiment, SUB experiment, and GTOP30 10 min topography, at (1) 30°N, (2) 35°N, and (3) 40°N, respectively. Similarly longitudinal cross-sectional topography at (4) 70°E, (5) 75°E, and (6) 80°E, respectively. (b) 1980–2001 averaged winter (DJF) precipitation (mm d$^{-1}$) (on left hand axis) and topography (m) (on right hand axis) along a latitudinal cross-section at (1) 30°N, (2) 40°N, and (3) 45°N and a longitudinal cross section at (4) 70°E, (5) 75°E, and (6) 80°E. CONT-Pr and CONT-Topo correspond to control precipitation and topography, respectively. Similarly SUB-Pr and SUB-Topo correspond to subgrid experiment. CRU-Pr corresponds to CRU precipitation. APH-Pr corresponds to APHRODITE precipitation (for details please refer Dimri and Niyogi, 2012).
tropospheric transient vortex providing a strong barotropic shear (Krishnamurti et al., 1981) associated with ISM situated over northwest India. This vertical shear of the vortex was instrumental in bringing additional moisture over the Leh region (Rasmussen and Houze, 2012). Kumar et al. (2014) hypothesized that mesoscale convective systems associated with cloudburst events were steered towards the Leh region by the 500 hPa wind, and low level moist air from the Arabian Sea and Bay of Bengal rose up to the Himalayan barrier. The corresponding rainfall intensity reconstructed from the flood hydrographs showed a very high intensity rainfall up to 320 ± 35% mm constrained over a 1.6 km² area for 8.8 min and 209 ± 35% mm rainfall over 0.842 km² for 11.9 min (Thayyen et al., 2013).

Another such event occurred on 13 September 2012 over the Ukhimath, Uttarakhand, in the central Himalayas. The Ukhimath region is situated on the protruding foothills of the central Himalayas valley floors having an opening towards southwest on both sides. Shrestha et al. (2015) showed the development of an easterly low-level wind along the Gangetic Plain caused by a low pressure system over the central Gangetic plain. This situation led to the convergence of moisture over the north-western part of India, hence an increase of potential instability of the air mass along the valley recesses, which was capped by an inversion located above the ridgeline and strengthening of the north-westerly flow above the ridges. This supported the lifting of potentially unstable air over the protruding ridge of the foothills of the Himalayas and triggered a shallow convection that, on passing through adjacent topographic folds, initiated a deep convection.

With specific elaboration on the cloudburst dynamics, a brief preamble with a case study of 13 September 2012 cloudburst over Ukhimath in the central Himalaya is provided. This case was studied with a Consortium of Small-scale Modeling (COSMO) (Doms and Schaettler, 2002; Steppler et al., 2003; Baldauf et al., 2011) at spatial scale of 2.8 km in the convection permitting mode (COSMO-DE). Comparison of the spatial pattern of precipitation field by the model with the corresponding observation of the Tropical Rainfall Measuring Mission (TRMM) 3B42 (V7) showed that the model underestimated the extent of daily accumulated precipitation compared to the corresponding observations. However, a consistent spatial pattern for the precipitation maxima along the lower and upper foothills of the Himalayas (Fig. 3a and b) is seen. The modeled daily accumulated precipitation over this area along with its complex topography at a 2.8 km resolution is shown in Fig. 3c. The model simulated cumulative maximum daily precipitation for this cloudburst event was up to over 200 mm/day (Fig. 3d). It can be seen that the zone of maximum precipitation shifted somewhat from the Ukhimath and it was consistent with the corresponding TRMM observations. In the model environment, precipitation started around 1700 UTC (+0530 LT) and reached its peak by the midnight of 13 September 2012. The modeling of this particular event, specifically the probable location and time of the associated maximum, has helped in better understanding the process associated with cloud burst events that are otherwise elusive due to their occurrence in remote regions of the Himalayas.

In the case of tropical cyclone-led flooding on 2 May 2008 in Myanmar, cyclone Nargis made a landfall, causing a worst natural flood disaster. The geomorphological situation of the Myanmar with the Khasi and Jaintia hills, an extension of the Himalayas, is important to mention here. Cyclone Nargis was of category 4 on the Saffir-Simpson Hurricane Scale (Fritz et al., 2009). Sustained winds of the order of 210 km/h, with gusts up to 260 km/h, persisted before the landfall on 2 May 2008. Due to increased convection owing to the influence of ITCZ and cyclonic circulation, a low-pressure system formed over the Bay of Bengal. Due to the warmer oceanic condition, lower vertical shear and pole-ward outflow, a deep depression developed (Raju et al., 2012). On account of the positioning of anticyclone in its west this storm steered northwest, intensifying as a cyclonic storm. Based on the flood direction, inundation distances reached up to 50 km inland from the nearest coastline. The atmospheric mechanism leading to flash flooding in this case was different from the case of cloudburst discussed above. In this case, tropical cyclone formation and interaction led to subsequent flooding, whereas in the above cloudburst case convective driven mechanism locked with the orography led to flooding.

2.4. Large scale atmospheric flow conditions

Four of the most devastating floods (Pakistan 2010, Uttarakhand 2013, Kashmir 2014 and Brahmaputra 2012) in the Himalayan region in the recent past resulted from torrential rains associated with large

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**Fig. 3.** (a) Daily accumulated precipitation on 13 Sept. 2012 from TRMM 3B42 data, (b) Daily accumulated precipitation on 13 September 2012 simulated using COSMO (D2 domain). The two bands of precipitation are outlined, along with the borders of Uttarkhand state, (c) Zoomed modeled accumulated precipitation with the local topography at the resolution of D2 domain (2.8 km). The topography contour interval is 500 m, from 2000 to 6000 m elevation, (d) Time-series of accumulated precipitation at location marked “o” and the surrounding grid cells, starting from 12 Sep. 2012. The precipitation accumulation for spatial plot is from 0000 UTC to 2330 UTC (Shretha et al. 2015).
scale atmospheric flows, where monsoons played a major role. The occurrence of the 2010 Pakistan flood was due to the interaction of tropical-extratropical flows linked with the European blocking (Webster et al., 2011; Houze et al., 2011; Lau and Kim, 2012). This July–August 2010 flood was the worst over the Pakistan region. On 28 July 2010 the mid-tropospheric 500 hPa height deviated from its monsoonal normal conditions (Houze et al., 2011). This anomalous condition brought in dry air into the western Himalayan foothills from the Afghan plateau. In tandem with such a situation, a low pressure monsoon system over the Bay of Bengal brought in very humid deep layer of moisture wind leading to a major rain storm. Hong et al. (2011) have shown the role of large-scale circulation perspective in strong tropical-extratropical interaction due to the coupling of monsoon surges and extratropical wave activity downstream of the European blocking. The teleconnection of Russian Heat wave and Pakistan flood is important (Lau and Kim, 2012), generating anomalous southwesternly flows along the foothills of the Himalayas in association with northward propagation of the monsoonal intraseasonal oscillation brought in abundant moisture transport from the Bay of Bengal. Such exceptionally huge deluge can possibly be predicted using an Ensemble Prediction System.

In another case, a large scale atmospheric flow in the central Himalayan region caused one of the most devastating extreme rainfall and flood events over upper Ganga basin of Uttarakhand during 16–17 June 2013. The monsoonal low pressure system, providing increased low level convergence and abundant moisture, interacted with the mid-level westerlies and generated a strong upper level divergence. Such interaction led to a faster northward progression of the monsoon ITCZ to cover the entire Indian sub-continent and yielded heavy rainfall over the region (Joseph et al., 2014; Chevuturi et al., 2015). The large scale wind and geopotential height variation at low, mid and upper tropospheric levels is shown in Fig. 4. The figure depicts curved southwesternly flow associated with the ISM at 850 hPa. This is a cross-equatorial flow termed as low level jet (LLJ) (Blanford, 1884; Joseph and Raman, 1966; Findlater, 1969) and has a direct relation with monsoonal rainfall over peninsular India (Joseph and Sijikumar, 2004). The LLJ is responsible for the moisture transport which is required for sustaining the storm (Figure not presented, refer Chevuturi et al., 2015). Moisture incursion over the Indian sub-continent during 15–16 June 2013 is from Arabian Sea and Bay of Bengal. On 17 June 2013 there is additional moisture flow from Arabian Sea, which is also reported (Ranalkar et al., 2015). The monsoon depression in the figure strengthens as it moves northwards in the successive time periods. In the upper-troposphere, a trough is seen in the subtropical westerly jet (STWJ), which extends till the north-western India. This is the western disturbance (WD) travelling in the STWJ and its axis shows a slight eastward movement in the different time steps. It is seen as the confluence of the two systems: monsoon trough of ISM and WD in the STWJ occurs on 17 June 2013. Considering the two systems are present in the lower and upper parts of troposphere respectively, this merging could have extended right from lower to upper-troposphere. At 500 hPa, a trough with a deeper extent than the WD is observed. This trough is showing the merged low pressure zones of both monsoon trough and WD trough. This trough is the cause of the transient cloud system, formed along the same axis centered over Uttarakhand. The corresponding observations (MERRA dataset) of large scale wind and geopotential height show similar results (figure not presented, refer Chevuturi et al., 2015). Singh et al. (2015) illustrated the active phase of Madden Julian Oscillation (MJO) that led to the faster northward propagation of the monsoon ITCZ. In the case of the Jammu and Kashmir floods of 2014 and 2015, a southward extension of western disturbances (Dimri et al., 2015) and its merging with the monsoon core was the major cause for the torrential precipitation leading to one of most severe floods in the region.

Some general characteristics of orographic rainstorms have been elaborated by Houze et al. (2011). Rainstorms over the mountains result when air is lifted over the terrain. In an unstable environment, a downdraft occurs in a rainy region. When sequences of such convective up and down drafts occur, the precipitating cloud system takes on the form of mesoscale convective system (Houze et al., 2011). During this process, some convective cells disintegrate, while new ones emerge. The older dying storms group together to form regions of stratiform rains. On the upslope side of the Himalayas, mountains can sustain mesoscale convective systems, as the airflow over the rising terrain triggers new intense convective cells, thus sustaining mesoscale convective systems for longer periods and the orographic upward air motion may sustain and broaden the stratiform region of the mesoscale convective systems. Such conditions are suggested to be the mechanism of extreme rainfall in the eastern Himalayas (Houze et al., 2007) and is suggested as the mechanism behind the 2010 Pakistan flood as well. Further studies in this direction will improve our understanding of extreme rainfall across the Himalayas.

3. Predominant land surface processes in Himalayan flood generation

The Himalayan terrain and processes shaping the land surface strongly influence and are, in turn, influenced by flood generation and propagation. By monitoring atmospheric moisture, routing surface runoff, and controlling the supply of sediment/debris, the landscape of the Himalayas and its influence on alloyclic and autocyclic response is a first-order control to fluvial processes, including flooding. Given the varied flood-generating mechanisms related to the Himalayan topography and patterns of geologic uplift and weathering, we present three broad categories for the origin of Himalayan floods: (1) atmospheric origin, (2) floods of cryospheric origin, and (3) floods of geologic/geomorphic origin. Because flood events are often a product of interaction across these categories, we also discuss hybrid floods generated by combined effects (Fig. 5).

3.1. Floods of atmospheric origin

3.1.1. Floods from large scale monsoon flow and topography controls

A large swath of the Himalayas comes under the monsoon flood zone, extending from Kashmir in the west to the eastern frontiers of the Himalayas (Fig. 1). Annual floods driven by monsoon rainfall are a nearly universal signature of the Himalayan rivers. River channels are shaped by annual peak flows that may be of the orders of magnitude greater than the mean annual flows (Kale, 2003). One of the major factors controlling rainfall intensity across the Himalayas is the mountain topography (Nandargi and Dhar, 2011; Bookhagen and Burbank, 2010). Moisture is pushed up by the mountain barrier and this upward trajectory is regulated by the mountain slopes. Hence, precipitation occurrence along the major parts of the Himalayan arc is concentrated in distinct orographic bands (Bookhagen and Burbank, 2010). One of these bands is along the lower ranges of the Siwaliks. Major extreme one-day rainfall is mainly reported from an altitude > 1000 m above sea level along the foothill zone (Nandargi and Dhar, 2011). The central Himalayas are characterized by a two-step topography, where two distinct relief zones of the mountains, represented by the lesser Himalayas and the greater Himalayas, aiding the orographic lifting of the monsoon moisture and resultant higher rainfall 10’s of kilometers offset to those relief zones (Fig. 6). On the other hand, western Himalayas are mainly characterized by a one-step topography, in which only one major mountain relief facilitates the orographic lift and the corresponding higher rainfall. Precipitation observed by the TRMM reveals higher annual rainfall along this dominant mountain relief (Bookhagen and Burbank, 2006; Bookhagen, 2010; Bookhagen and Burbank, 2010).

In the monsoon flood zone (Fig. 1) inputs of summer monsoon precipitation dominates the annual water budget, with snowmelt as a secondary contribution (Bookhagen and Burbank, 2010). Thus, most of the geomorphic draining by the eastern and central Himalayan rivers occurs during the summer monsoon flood season, while more than 80% of the
annual rainfall across the central Himalayas and Ganges Plain occurs during the monsoon season (Bookhagen, 2010) and <50% of annual rainfall occurs during the monsoon season in the western Himalayas. Additionally, in contrast to the eastern and central Himalayas, a large proportion of runoff from the western Himalayan rivers is comprised of snowmelt, which is beyond the scope of this study. Bookhagen and Burbank (2010) estimated snowmelt contributions of 66% and 57% in the Indus and Sutlej basins, respectively, while reporting that water budgets in the central and eastern Himalayas comprise <20% snowmelt. Reflecting the varied water phases across the western Himalayas, there are often two associated discharge peaks that occur during the summer monsoon, a less intense earlier peak attributed to combined snowmelt and rainfall and a more intense later peak primarily due to monsoon rainfall (Pal et al., 2013). In addition to the elevation gradients in the mean annual rainfall across the Himalayan orography, the percentage of rainfall that occurs during the monsoon season is regionally variable. Bookhagen and Burbank (2010) reported gradients of monsoon precipitation, where monsoon rainfall decreases, moving west from the Bay of Bengal.

In the central Himalayan region, annual rainfall amount is concentrated below 500 m above sea level, whereas in the western and eastern regions this elevation zone extends from 500 to 4000 m above sea level. Overall, the highest annual rainfall occurs in the eastern region. Flood severity at the foothill zone is also possibly linked with the rainfall distribution regulated by the mountain topography. This east to west decrease in the rainfall amount is also reflected in the peak flood discharge. However, peak erosional processes, which trigger landslides, rockfalls, debris flows, and other mass movements, occur deep within the orographic interior frequently triggered by rainfall (Wulf et al., 2010).

In this discussion on floods, particularly related to the large-scale atmospheric flow, a case study of the recent Uttarakhand flood of 2013 is discussed. Fig. 7a–d shows different vertical distributions related variables whose physical and dynamical processes associated with the flood storm are discussed here. On day 1, 16 June 2013, an increasing low level relative humidity is seen from 0600 UTC to 1800 UTC (Fig. 7a), which in mid to upper-troposphere increases after 16 June 2013 1200 UTC (Fig. 7a). An increase in the associated vertical wind is also seen (Fig. 7a). The higher low level moisture is due to the moisture incursion from the Arabian Sea (figure not represented) along with the low level jet in the monsoonal south-westerly flow. It is seen that the monsoonal convergence zone moved faster northwards in this particular year. This
increased moisture reached the Uttarakhand region, in association with the increased vertical wind that led the low level moisture to rise up-slope mountains and rise up to mid and upper-tropospheric levels. The sudden rise of moisture in the water vapor form was forced to go through various microphysical processes, thus forming different hydrometeors, viz., cloudwater, cloud ice, rainwater, snow and graupel (Pruppacher and Klett, 2010). The signature of these hydrometeor concentrations and the corresponding mixing ratios and the hydrometeor dependent reflectivity signifies the formation of clouds over the region (Fig. 7b). During the storm, two time slices are very distinctly seen with increased reflectivity: 16 June 2013 1200UTC and 16 June 2013 1800UTC onwards. Though there was continuous rainfall reported throughout the time period, however, during these two distinct time periods due to increased hydrometeor formation first and second heavy precipitation episodes occurred one before (16 June 2013) and second during (17 June 2013). These two episodes brought in the cascading effect for the Uttarakhand disaster. Further investigation with the corresponding vorticity and divergence (Fig. 7c) showed a low level positive vorticity on 16 June 2013 that led to the development of instability in the region due to the monsoon trough of ISM. The positive

Fig. 5. Various types of flood generating mechanism in the Himalayan region.

Fig. 6. Monsoon over Himalaya is driven by the orographic processes and mountain topography controls the precipitation distribution. Two step topography describes two distinct relief of the mountain aiding higher precipitation 10 of kilometre offset to the relief. Regions with one step topography have only one major relief and corresponding higher precipitation zones. These higher precipitation zone are the potent source areas of Himalayan flood. (Source: Bookhagen and Burbank, 2010).
vorticity on 17 June 2013 dominated in the mid-troposphere. This remained the zone of confluence of western disturbance and monsoon trough. The low level convergence and upper tropospheric divergence led to increased vertical winds and disturbance in the subtropical westerly jet, providing the divergence aloft. The convective lifting in tandem with orographic forcing invigorated the storm. As precipitation patterns were reported to be increasing from 16 June 2013–17 June 2013 (data not presented), the corresponding model convective available potential energy between 16 June 2013 0600UTC and 1200UTC was also seen to be increasing (Fig. 7d). Thus, storm intensification was promoted from 16 June 2013 1200UTC onwards, which was subsequently suppressed due to higher convective inhibition.

3.1.2. Cloudburst floods

Floods that originate from precipitation associated with mesoscale convective events may differ from those related to large-scale monsoonal flows in terms of scale, concentration time, and duration. Though the scope of geographic impact may be limited, floods generated by high-intensity short-duration cloudburst events can be devastating and very difficult to predict or prepare for. Cloudburst is one of the least known mesoscale processes of the Himalayan region (Das et al., 2006; Shrestha et al., 2015) whose occurrence is seemingly increasing over this region. Table 1 shows the cloudburst events reported for the Himalayan region in the recent past. These storms and associated destruction have generated more attention to their corresponding physical processes these days. According to the India Meteorological Department (IMD) a cloudburst features a very heavy rainfall over a localized area at a very high rate of the order of 100 mm/h with strong winds and lightning. It is a remarkably localized phenomenon affecting an area not exceeding 20–30 km² (IMD, 2010). Though a few observed data document the hydrologic response to cloudbursts, the hydrologic signature of a cloudburst event may consist of extremely rapid hydrograph rise and fall within small catchments (Fig. 8d). However, a cloudburst is often associated with sustained low pressure system and associated rainfall over a wider region extending 2–3 days, as experienced in the Leh region in 2010, and the corresponding hydrograph response at larger basin scales may be muted and lagged (Fig. 8c). Because of the highly localized nature of cloudburst, antecedent soil moisture conditions play a little role in determining the flood severity. It is often suggested that a cloudburst occurs in a catchment with steep topography (Das, 2005). Such steep topography could also be a factor in determining the flood hydrograph, including time to flood peak and flow velocity. A detailed study of the cloudburst in the Leh region in 2010 (Thayyen et al., 2013) showed that cloudbursts could result in a very high peak discharge ranging from 545 ± 35% m³/s from a 2.83 km² catchment to a 1070 ± 35% m³/s from a 64.95 km² catchment. It was reported that the flood duration under such conditions was as low as 01 h. The study pointed towards limited possibilities for the success of forecasting such events. Even with the state-of-the-art Doppler radars, forecasting cloudburst locations would be a big challenge. A cloudburst often impacts the mountain slopes of the first order stream catchments with settlements, and the mountain population becomes at more risk from cloudburst floods than the floods of torrential rain origin. The control of land surface/topography on the formation of cloudburst cells has been discussed in recent studies (Chevuturi et al., 2015). There could be differences in the cloudburst flood hydrograph characteristics in an arid bare rock exposure region like Ladakh and a region with thick vegetation like Uttarakhand. The Ladakh region seldom
experiences antecedent precipitation but the rest of the Himalayas under the monsoon regime have hardly any soil moisture deficiency during the cloudburst period. Manifestations of these factors in the flood hydrograph characteristics are least known land surface controls on the cloudburst floods. Repeated occurrences of cloudbursts on a particular catchment clearly point towards the control of the mountain slopes on the cloudburst formation (Thayyen et al., 2013). Hence, the disaster risk reduction option in response to the cloudburst floods is limited to the settlement management. It is noticed that most of the causalities in such cases occur over settlements in the paleoflood/dry channels (Thayyen et al., 2013).

3.2. Floods of geologic origin: Landslide Dam Outburst Flood (LDOF)

Geologic and geomorphic processes associated with steep landscapes of the Himalayan region, which is tectonically highly active, could facilitate massive floods due to the occurrence of landslides into the river leading to river blockage. These types of floods are known as Landslide Dam Outburst Floods (LDOF) or Landslide Lake Outburst Floods (LLOF). Some of the worst floods in the region are caused by LDOF. River Indus experienced such a flood in 1841 known as the “Great Indus Flood”. As detailed in Mason (1929), the landslide was triggered by an earthquake in December 1840 or January 1841 on the west side of the Lechar spur of Nanga Parbat. By the beginning of June 1841 the water probably reached the top of the earthen dam, forming a 64 km long and 300 m deep lake. According to Mason (1929), the lake emptied in 24 h, devastating hundreds of villages and killing thousands of people. At Attok, more than one thousand kilometers downstream, the flood was about 92 ft high, whereas normal high flood level is 42 ft (Falconer, 1841).

The Upper Ganga basin under the monsoon regime is more prone to landslides and quite a few LDOF’s have been reported from two major
Himalayan tributaries of Bhagirathi and Alakananda. The earliest report of the LDOF in the upper Ganga basin dates back to 26 August 1894 (Holland, 1984; Rana et al., 2013). A landslide lake of approximately 270 m high and 3 km wide at the base was formed over Birahi Ganga River, which is a tributary of Alakananda River, on 6 September 1893. It is reported that this flood was managed by diverting the pedestrian routes and removing 08 suspension bridges on lower reaches. The Alakananda valley again experienced another major flood after 76 years in July 1970. It is believed to be initiated by a cloudburst between Joshimath and Chamoli (Rana et al., 2013). The 1970 flood resulted from the failure of a persistent lake formed in the 1893 landslide at Gohana. The 1970 flood washed away 30 buses and 13 bridges downstream, besides destroying roadside settlements. The Bhagirathi River and its tributary Kanoliya stream were blocked by a massive slide called Dabrani landslide on 6 August 1978, forming two lakes (Dinri and Pandey, 2014). The bursting of these natural dams later caused an immense loss of life and property. Though not much mechanism associated with these historical flood events, however, a brief discussion is provided due to the nature of their devastation.

Another recent and well-documented LDOF is the Pareecchu landslide dam in Tibet on 25 June 2005. The lake was created by a landslide that occurred on 08 July 2004 (Gupta and Shah, 2008). Generally, the areas of Tibet bordering India do not receive heavy rainfall and the landscape is completely barren. Hence, the trigger for this landslide is not very clear. Most recently, the Phuktal River in Zanskar got blocked by a heavy landslide that occurred on 15 January 2015 in a comparable arid topography (www.greaterkashmir.com). The location of the landslide lake was about 90 km interior of the road head and monitoring and managing this lake was a challenge. The National Remote Sensing Centre (NRSC), India, has carried out routine monitoring of this lake (www.nrsc.org). The lake had busted on 07 May 2015, affecting around 40 villages. These two LDOFs in the cold-arid region suggest a need for better understanding of the trigger of landslides in such areas. The role of permafrost thaw and snow melt water seepage in triggering landslides in such areas needs to be studied. The floods in the Seti River in Nepal had been suggested to be triggered by a rock slope failure at an altitude of 6700 m at Annapurna–IV which travelled through the southwest slope up to the river confluence (Bhandary et al., 2012).

The LDOFs occurred in monsoon and non-monsoon flood zones of the Himalayas indicating diverse landslide triggering mechanisms. Hence, a better understanding of factors triggering the mass movement in the Himalayas, especially under the climate change scenario, is needed for managing these floods.

The control of sediment supplies to rivers draining the Himalayas is highly influential to drainage network dynamics and channel morphology. Dominant autocyclic processes include both changes to channel morphology through flood cycles and stochastic land-forming events, such as gravity-driven mass wasting and dam break floods. Additionally, alloyclic events, notably related to seismicity, influence the periodic sediment supply. Though the channel responses and the geomorphic effects vary spatially, the most pronounced geomorphic effects of monsoon floods are over the Indian Himalayan region (Kale, 2003). There are numerous instances of flood-induced dynamic changes in the channel dimensions, position and pattern. As Himalayan rivers often carry vast quantities of sediment and debris (Kale, 2003), flows laden with material can be highly destructive and may require special preparedness measures for risk reduction. Additionally, generation of debris-laden flows entails different processes and conditions than those driving floods of atmospheric origin. Thus, forecasting such flows may require different approaches to monitor and model than those commonly applied to riverine flooding. Along the continuum spanning end members of pure water flows and those containing little water, such as landslides, researchers and managers classify flows of variable proportions of water and other materials (Postma, 1986; Hungr et al., 2001).

3.2.1. River avulsion

Foreland basins of the Himalayan rivers often take the brunt of floods generated by high mountains. River avulsion is one such phenomenon which could increase the disaster potential of a flood. Avulsion occurs when an aggrading river leaves its channel to pursue a lower-elevation course, thus producing a sudden flood scenario in the otherwise safe low lying areas away from the normal river course. Avulsion is often triggered at the flood stage (Jones and Schumm, 1999) and flood damages that occur when a river rapidly changes its course can be severe. Many Himalayan rivers have long histories of channels shifting through avulsion, especially in the alluvial foothill and plains’ reaches. Heavy sediment loads from actively weathering high-altitude zones are carried by high-gradient, powerful mountain rivers to deposit where valleys widen and channel slopes diminish. In these alluvial reaches, active aggradation associated with such deposition creates hazardous conditions for avulsion-related flooding. Due to the high frequency of such events relative to other regions, some Himalayan rivers are considered to be ‘hyperavulsive’ (Jain and Sinha, 2004).

The alluvial reaches of Kosi River, which has many times transitioned between channels in a wide alluvial fan, is a well-known example of avulsion phenomenon (Wells and Dorr, 1987). Most recently, following heavy monsoon rains in 2008, the Kosi River broke through man-made embankments to flow out of its channel (Sinha, 2009). It started flowing through an old channel 120 km to the east, inundating cropland and towns and villages with 1.2 million inhabitants, mostly in Bihar province of India. Over 30 million people were affected by this one avulsion related flood event. In this case, heavy monsoon precipitation triggered avulsion in the Kosi channel, yet the influence of river engineering works also contributed to the avulsion (Sinha et al., 2008; Sinha, 2009). As the origins of this event included interactions of atmospheric, hydrologic, and geomorphic variables and was likely influenced by human engineering of the river channel, traditional methods of flood forecasting would have been unlikely to predict such an occurrence. Paleochannels formerly occupied by aggravating rivers may be particularly hazardous.

3.3. Floods of cryospheric origin

3.3.1. Glacial Lake Outburst Floods (GLOF)

Non-monsoon floods in the Himalayas are mainly of cryospheric origin and spread across the trans-Himalayan region where monsoon penetration is least and at the higher altitude glacial regimes 3500 m above sea level in the monsoon zone (Fig.1). Floods of cryospheric origin in the Himalayas mainly occur due to Glacial Lake Outburst Flood (GLOF), glacial surge dam outburst flood and snow avalanche dam outbursts. The GLOF is the major flood generating mechanism of this genre. A glacial lake is defined as water mass existing in a sufficient amount and extending with a free surface in, under, beside, and/or in front of a glacier and originating from glacier activities and/or retreat processes of a glacier. Retreating glaciers in the Himalayan region have facilitated the formation of proglacial glacial lakes in the region. In recent years accumulation of water in these lakes has been increasing rapidly in the Himalayas (Ives et al., 2010). The glacial lakes are classified into Erosion (Valley trough and Cirque), Ice Blocked, Moraine Dammed (Lateral Moraine and End Moraine Dammed lakes), and Supraglacial lakes (Campbell and Pradesh, 2005). Inventory of glacial lakes in the Himalayan countries has revealed the existence of a large number of glacial lakes in the region. In the case of GLOF, the probability of occurrence mainly depends on the expansion rate of the glacial lakes, as well as the probability of ice/rocks falling into the lake (Richardson and Reynolds, 2000). The stability of damming moraines (Clague and Evans, 2000) and the failure of damming moraine (Fujita et al., 2013) are essential for the release of glacial lake water.

A GLOF is created when the water dammed by a glacier or a moraine is released suddenly. Some of the glacial lakes are unstable and most of them are potentially susceptible to sudden discharge of large volumes of
water and debris which cause floods downstream. These floods pose severe geomorphological hazards and can wreak havoc on all manmade structures located along their path. Much of the damage created during the GLOF events is associated with large amounts of debris that accompany the floodwaters. The lakes at risk are invariably situated in remote and often inaccessible areas. When they burst, the devastation to local communities could be tremendous. Due to extreme hazard potential, it is necessary to take into account GLOF, while planning, designing and constructing any infrastructure, especially water resources projects, bridges and culverts as they are located on the path of flood wave and would be the prime target for catastrophe.

It is observed that the number of GLOFs has increased in the Himalayas through the last century (Richardson and Reynolds, 2000). Previous studies have shown already that the risk of lake development is highest where the glaciers have a low slope angle and a low flow velocity or are stagnant (Quincey et al., 2007; Reynolds, 2000). Whether glacial lakes become dangerous depends largely on their elevation relative to the natural spillway over the surrounding moraine (Benn et al., 2000; Sakai et al., 2000). Triggering events for an outburst can be motive to the natural spillway over the surrounding moraine (Benn et al., 2000). The state of the Kumdan dam in 1928 (Ludlow, 1929) and its subsequent burst in 1929 is well documented (Mason, 1930). It has been reported that the Kumdan Lake was 16 km long, 120 m deep and stored around 1.5x10^9 m^3 of water blocked by 2.4 km ice barrier. After the breach, the lake water was evacuated in 48 h with an estimated peak discharge of 22,650 m^3/s (Hewitt, 1982). This flood resulted in a huge devastation in the Shyok valley and Indus up to 1194 km downstream (Attok) of its origin.

Glacial surges are not random events but cyclic phenomena, probably driven by the frozen and unfrozen conditions of the glacier bed (Murray et al., 2000; Fowler et al., 2001). Hence, surge dam outburst floods are a perennial threat for the regions inflicted by the glacier surge phenomena. However, proper monitoring of these areas can reduce the disaster potential of such lake outbursts considerably, as surge initiation, lake formation and its eventual failure give ample time for a calibrated response.

3.4. Floods of hybrid origin

Flood events in the Himalayas often are the product of multiple interactive geneses. Floods in the hybrid category are produced by rain or snow events, rain over glacial/periglacial lakes, earthquake-induced GLOF or LDOF, or earth burst – a phenomenon of sudden outflow of water from the earth usually along the mountain slope which is accumulated over days of continuous rain over the region during the monsoon and is a relatively unknown phenomenon.

One of the most devastating recent examples of a hybrid flood is the June 2013 flood of the upper Ganga basin, including Kedarnath area of Uttarakhand. During the Kedarnath floods, the entire upper Ganga basin from Haridwar to Kedarnath experienced floods during 15–17 June 2013. These floods were one of the worst in this region, causing severe loss of life and property-killing around 6000 people and damaging innumerable roads and bridges and adversely affecting 30 odd hydro-power plants (Allen et al., 2015). Widespread rains across the state of Uttarakhand and nearby plains caused by an anomalous advancement of ITCZ associated with ISM that led to high-intensity torrential rains. This extreme precipitation was caused by pulsed extension of the monsoon trough with interim support from an existing unusual western disturbance, which was the key driver of accelerated northward advance of the ISM convergence zone (Chevuturi and Dimri, 2015). The rainfall, recorded during 14–18 June 2013 period, averaged over a wide swath of the region, was 364 mm (Durga Rao et al., 2014). The highest recording station in the area above Kedarnath at 3820 m above sea level recorded 325 mm rainfall in 24 h interspersed between 15 and 16 June 2013 (Dobhal et al., 2013). The widespread sustained rainfall caused floods in the downstream reaches of the Alaknanda and Bhagirathi Rivers. The Kedarnath temple, one of the most revered Hindu pilgrim sites at 3800 m above sea level, was hit by the floods first on 16 June 2013 evening caused by the torrential rain falling over the extensive snow cover (Dobhal et al., 2013). This rain on snow event fed huge quantities of water into the periglacial Chorabari Lake situated at 3960 m above sea level near the Chorabari glacier which resulted into the bursting of this lake during the early morning hours of 17 June 2013, killing scores of pilgrims and devastating the Kedarnath temple and downstream areas. One of the factors that worsened this extreme event was the antecedent precipitation/snow melt which ensured the slope saturation before the actual event (Allen et al., 2015; Durga Rao et al., 2014). This event has demonstrated extreme possibilities of hybrid Himalayan floods and their disaster potential.
close to the earth burst zones who are witnesses to the water bursting out of the earth. One of the known events of earth burst occurred in the Hinval catchment in the middle Himalayas of Uttarakhand on 15 Aug 2014. The event, earlier thought to be a cloudburst flood, turned into an earth burst event after surveying the people living close to the site. Such events are common along the Western Ghats of Kerala and there are some studies detailing these phenomena (Kurikose et al., 2006). However, the occurrence of such events is not common in the monsoon dominated regions of the Himalayas. This indicates that the lack of understanding of the various earth flood generating mechanisms is limiting the scope of effective flood management in the Himalayas.

4. Challenges and pathways to monitoring, predicting, and preparing for Himalayan floods

The varied nature of flood hazards in Himalayan Rivers necessitates a multi-faceted and multi-scaled action towards preparedness. The processes and phenomena need to be monitored, predicted, and disseminated. These actions need to transcend traditional disciplinary boundaries, requiring unified and collaborative efforts across various levels of government and administration between scientists, decision makers, and civil society. The relevant scales of Himalayan hazards trend towards global extremes, for instance, in terms of precipitation intensities, frequencies of active tectonics, flood discharges, sediment yields, land areas inundated, and number and vulnerability of peoples affected. Despite the high impact of Himalayan flood hazards, geographic and topographic constraints impede robust monitoring. In the case of transboundary rivers, lack of robust mechanisms for monitoring and sharing of hydro-meteorological data between the nations hamper affirmative actions.

The remote, rugged, and high-altitude source areas of many flood disasters (GLOF, LDOF, cloudbursts) confer limited access for ground-based data collection and thus have traditionally been some of the most poorly monitored places on the Earth. In-situ precipitation and river gauging stations are limited across the rugged terrains of the Himalayas, especially along the steep ridges of valleys where intense convection is likely to occur (Thayyen et al., 2013). Over recent decades, satellite observations and coupled hydro-meteorological modeling have improved characterization of flood hazards and understanding of interactive precipitation and topographic mechanisms over the Himalayas. An extensive inventory of benign and potentially dangerous glacial lakes across the Himalayas is synthesized based on satellite information (ICIMOD, 2010). Furthermore, a better understanding of the meteorological and atmospheric mechanisms generating extreme monsoonal precipitation events causing floods is provided (Barros et al., 2004; Barros and Lang, 2003; Das et al., 2006; Houze, 2012). In addition, there are a number of landslide hazard assessment tools which use remotely-sensed data to predict potential LDOF (Pardeshi et al., 2013).

Despite the promise of remotely-sensed data and modeled forecasts, without observed data to anchor predictions, such tools may be limited in their application. Without robust ground-based data upon which remotely-sensed data or hydrological models may be calibrated or validated, uncertainty associated with remote rainfall observation and hydrological prediction will be high. Flood modeling and management applications are severely limited by the coarse spatial and temporal resolution of remotely-sensed datasets. Only a few gridded remotely-sensed datasets (e.g. TRMM 3B43RT) have sub-hourly, 3-hourly, temporal coverage, and most are limited to a 0.25 × 0.25° spatial coverage. These products are spatially and temporally resampled from finer resolved satellite data. Using hydrologic reanalysis in the Ladakh region, Thayyen et al. (2013) estimated a storm depth of 320 (± 35%) mm which took place in 8.8 min in a small catchment (0.842–1.601 km²) of the Ladakh region. Harris et al. (2007) revealed the limitations of real time gridded satellite rainfall products in dynamic 1-dimensional flood modeling of small catchments due to its coarse grid size. Furthermore, numerical weather prediction models are unable to capture the precise location of highly convective cloudburst events (Das et al., 2006). In addition, the spatial resolution of topographic data across the Himalayas is limited to 30 × 30 m further limiting the application of 2-dimensional flood modeling.

Ground-based precipitation radar in the Himalayas is constrained due to the steep terrain, and precipitation radar from space holds promise to overcome this obstacle for making regional-scale precipitation observations. However, the uncertainties of precipitation radar observations are dissimilar across the orography (Duan et al., 2015; Wilson and Schreiber, 2015). Furthermore, precipitation radar observations are not available in real time. The sub-grid spatial distribution of precipitation is wider for gridded precipitation observations and is poorly defined. These sub-grid uncertainties are dependent on the atmospheric and land surface processes. Detailed analyses, which include ground-based precipitation observations to identify sub-grid spatial and temporal characteristics of rainfall across the orography, would be fruitful for the development of uncertainty estimates. There have been a limited number of short-term basin scale studies across the Himalayas in which a dense number of precipitation stations were deployed (Barros et al., 2000).

Many Himalayan rivers are transboundary watercourses and flood hazards often cross national boundaries and affect more than one country. Hence, cooperation regarding water-related disaster risk reduction and communication of hydrometeorological conditions between riparian river basins must be a shared priority. As of now, minimum advanced warning of hazardous conditions at upstream is being provided for hazard mitigation efforts in the downstream countries. However, formally-agreed procedures for sharing detailed ground and satellite based hydrometeorological data in real time are likely to generate the most impactful and just outcomes with regard to advanced preparedness. When river basin riparians lack procedures for direct exchange of observed hydrometeorological data, forecasters may face great uncertainty in the ‘geopolitically ungauged’ catchment areas outside their administration. Programs intended to enhance basin wide cooperation, including data sharing, in Himalayan river basins, such as the Hindu Kush–Himalayan Hydrologic Cycle Observing System (HKH-HYCOS) are notable pathways to remove geopolitical barriers to flood risk reduction.

Basin scale flood source area zonation has a great value for disaster risk reduction efforts, including flood forecasting. Among the major types of Himalayan floods listed earlier, cloudbursts, GLOF, glacier surge dam outburst flood, debris flows, and earth bursts are bound to impact the first order streams of the Himalayan slopes (Fig. 9). Designing Disaster Risk Reduction (DRR) strategies to deal with such floods are the major challenges due to very limited lead time and unknown source areas, especially for cloudbursts and debris flow including earth bursts. Potentially dangerous glacial lakes can be identified, but extremely short lead time in a GLOF situation (Fig 7g and h) and challenges associated with regular monitoring of such high altitude lakes make forecasting a big challenge. The middle reach of the Himalayan trunk channel is among the safest areas as far as the flood is concerned, as it flows through deep gorges most of the time (Fig. 9) away from human settlement. The downstream floods mainly generated from the torrential rains over a large area of the mountain can be forecasted effectively, as it provides a significant lead time (Fig. 8a and b).

The topographic control over the orographically uplifted monsoon rains provide another opportunity to constrain the monitoring efforts along the two highest precipitation zones assisted by the two-step topography. In a study carried out in the Chenab basin, this important aspect is demonstrated. Chenab basin comes under the one step topography regime where monsoonal precipitation occurs along the first orographic barrier in the basin. Rainfall is monitored in the Chenab basin at 21 stations and there are 09 discharge stations in the basin. Studies have shown that the source areas of all the major floods in the Chenab basin is restricted to lower 7269 km² area (Fig. 10). It is observed that the floods are actually gaining strength while passing
Fig. 9. Flood impact zones in the upper Ganga basin. Recent cloudburst/lake burst often impact the first or second order streams in the mountain slopes, mainly impacting the settlement along the valley floor. Floods from torrential rains impact the foothill zones. The trunk river in the mountain reach often flow through deep gorges posing limited risk.

Fig. 10. Floods in the Chenab basin is generated from one step topography. (a) Hydrograph of some major floods in the Chenab river at Akhnoor (b) generated from the lower most zone constitutes Shivaliks mountain acting the first orographic barrier for monsoon winds blowing from the south-west. (c) distribution of seven rainfall measuring stations in this lower zone and location of representative station of Paoni.
through the last three discharge stations (Fig. 10a and b). Seven rain gauge stations in this constrained area are found to be representing the extreme torrential rainfall responsible for the floods and the studies even narrowed down to one station representing the regional extremes of the rainfall (Fig. 10c). This suggests that the spatial data generation, research and mapping of flood source zones can be very useful for forecasting and managing the monsoon floods from torrential rains in the region. Disaster potential of floods generated by the torrential rains over the mountains extends to the foothills zones further downstream (Fig. 9) (Ref. Koshi flood, Brahmaputra floods). Floods in the Brahmaputra River bring in huge devastation in Assam and Bangladesh further downstream and has been generated by torrential rains over steep mountain slopes and surrounding areas.

Catastrophic flooding in the downstream reaches of Brahmaputra River was caused by the simultaneous peaking of floods in the Ganges and Brahmaputra Rivers (Fig. 8e and f), providing the best example of complexities associated with the downstream flooding in the big basins with significant mountain area. Due to higher transit time, these floods can be effectively forecasted, if robust forecasting systems are in place and minimize the flood risk with effective intervention by the local government. Understanding of the seasonal distribution of floods across the Himalayan arc is also important for effective flood management by the administration. In the western part, floods from cloudbursts are expected in the month of July and August and the GLOF’s probability is high during August and September months. In the Kashmir region most of the major floods in the River Jhelum have occurred in the month of May and September. Of late, more cloudburst events are reported from the Kashmir region as well as experienced during the July and August 2015. In the central and eastern Himalayas, flood management effort can be focused during the monsoon months of June, July and August.

5. Conclusions

Himalayan floods are generated from various atmospheric, cryospheric and geologic processes and are highly influenced by the topography. Floods in the Himalayas have varying genesis and scale, linked to atmospheric, cryospheric and geological processes. Most frequent flood events in the Himalayas are associated with monsoon precipitation, either from torrential rains or from local convective events. Associated precipitation mechanisms and manifestations of these two rainfall types are entirely different from each other. The Himalayan arc orography plays a very dominant role in defining the associated dynamics of precipitation mechanism. Steering of atmospheric flow due to the variable topography and heterogeneous land use determines the scale and quantity of the precipitation. Hence, the Himalayan arc geomorphology is one of the key parameters determining the flood type and severity. A composite understanding is required for flood management but is lacking in the region.

Since a large population lives in the foreland basins of the Himalayas, socio-economic impacts of the large Himalayan floods are huge. Himalayan floods often lead to the loss of life, property, livelihood, health and epidemic and leave deep scars in the social and economic fabric. While forecasting capability of extreme events associated with large-scale monsoon flow is increased in tandem with the advancements in the weather satellite technology, ground based flow monitoring, flood forecasting remains as the area of huge concern in the Himalayas. Further, lack of understanding of the cloudburst processes, tracking and monitoring facilities and capabilities remain a huge challenge. It is observed that the cloudbursts are only recorded or reported when they cause damages to life and property and occur in the vicinity of a populated area. Hence, it is impossible to assess whether such incidents are increasing in the recent past due to changing climate. This seriously impacts our understanding of the causative factors of such extreme localized events. Hence concerted efforts to assimilate these disciplines are imperative for developing a robust flood management system for the Himalayan region.

Acknowledgments

Authors acknowledge the funding from Indo-US Science and Technology Foundation (IUSSTF) to organize “Indo-US Bilateral Workshop on Modeling and Managing Flood Risks in Mountain Areas” during 17–19 Feb. 2015 Folsom, Sacramento, CA, USA. The paper is part of the outcome of workshop deliberations.

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