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Orographic control of the Kedarnath disaster

The 2013 calamity in Uttarakhand is considered as India's worst natural disaster since the December 2004 Indian Ocean tsunami. Heavy, continuous rains have caused unprecedented damage to life and property where torrential rivers from the Himalaya swept away roads, bridges, houses and buildings in the swirling waters. According to the government officials, more than 1000 persons are expected dead with more than 6000 missing and tens of thousands have been displaced (http://www.indian-express.com; http://www.nytimes.com). The torrential rainfall between 15 and 17 June 2013 flooded the area causing excessive gulley erosions and sediment deposition on its way. It is suggested that during the night of 16 June 2013, due to incessant precipitation, large volume of water carrying huge amount of sediments, and debris from glacial moraines and surrounding areas struck Kedarnath town and washed off its upper parts[1]. The main reason for such voluminous flow is a breach in the snow melt and rainfed Chorabari Lake (3960 m amsl, approximately 400 m long, 200 m wide, 15–20 m depth) also known as Gandhi Sarovar Lake, which was dammed by the moraines deposited by Chorabari glacier (Petley: http://blogs.agu.org/landslide-blog/). The pressure of millions of gallons of water caused the breach in the loose-moraine dam resulting in glacial lake outburst flow (GLOF).

Various reasons have been put forward for this calamity. Some suggest this event occurred due to flash floods and others are in favour of a cloud burst. Dubey *et al.*[2] suggested that more than 200 mm of rainfall in 24 h in the mountainous terrain could be considered as a cloud burst which can trigger landslides. While Nandargi and Dhar[3] considered rainfall of more than 250 mm in 24 h as an extreme event in the Himalayan setup. In either case, the rainfall measured by India Meteorological Department (IMD) at Dehradun (approx. 300 mm in 24 h) and Wadia Institute of Himalayan Geology (WIHG) meteorological observatory at Chorabari Glacier camp (325 mm in 24 h) for this event can easily classify it as a cloud burst which has occurred as an extreme event.

There have been various events in the past where life and property have been damaged due to hydro-meteorological calamities in the Himalaya[4,5] (Table 1)[6–11]. In the Himalaya, during the period 1871–2007, out of 475 rain gauge stations, 357 have recorded one-day extreme rainfall events in excess of 250 mm, which are mostly located between the Siwaliks and the Higher Himalayan ranges[3]. Most of these extreme events happen either in the south of the Higher Himalaya or at the foothills of Siwaliks. South of the Higher Himalaya lies in the Lesser Himalaya zone, bounded by the Main Central Thrust (MCT) to the north and the Main

Table 1. Recent events of extreme rainfall, major flash floods and cloudbursts in the Himalaya

Type	Date	Month	Year	Affected area
GLOF/flash flood[6]	31	July	1991	Maling, Himachal Pradesh
Landslide[6]	24	February	1993	Jhakri, Himachal Pradesh
Flash flood[6]	11	August	1997	Tehsil, Himachal Pradesh
Cloudburst[2]	9	June	1997	Chandmari, Sikkim
Extreme rainfall/landslide[7]	11–19	August	1998	Guptkashi–Rudraprayag, Uttarakhand
Cloudburst/landslide[8]	16	July	2001	Rudraprayag, Uttarakhand
Cloudburst[9]	31	August	2001	Tehri, Uttarakhand
Cloudburst[10]	10	August	2002	Tehri, Uttarakhand
Cloudburst[11]	16	July	2003	Kullu, Himachal Pradesh
Extreme rainfall[3]	17	July	2004	Pasighat, Arunachal Pradesh
Cloudburst[3]	6-8	August	2010	Leh, Ladakh, J&K
Cloudburst[4]	18–19	September	2010	Almora and Pithoragarh, Uttarakhand

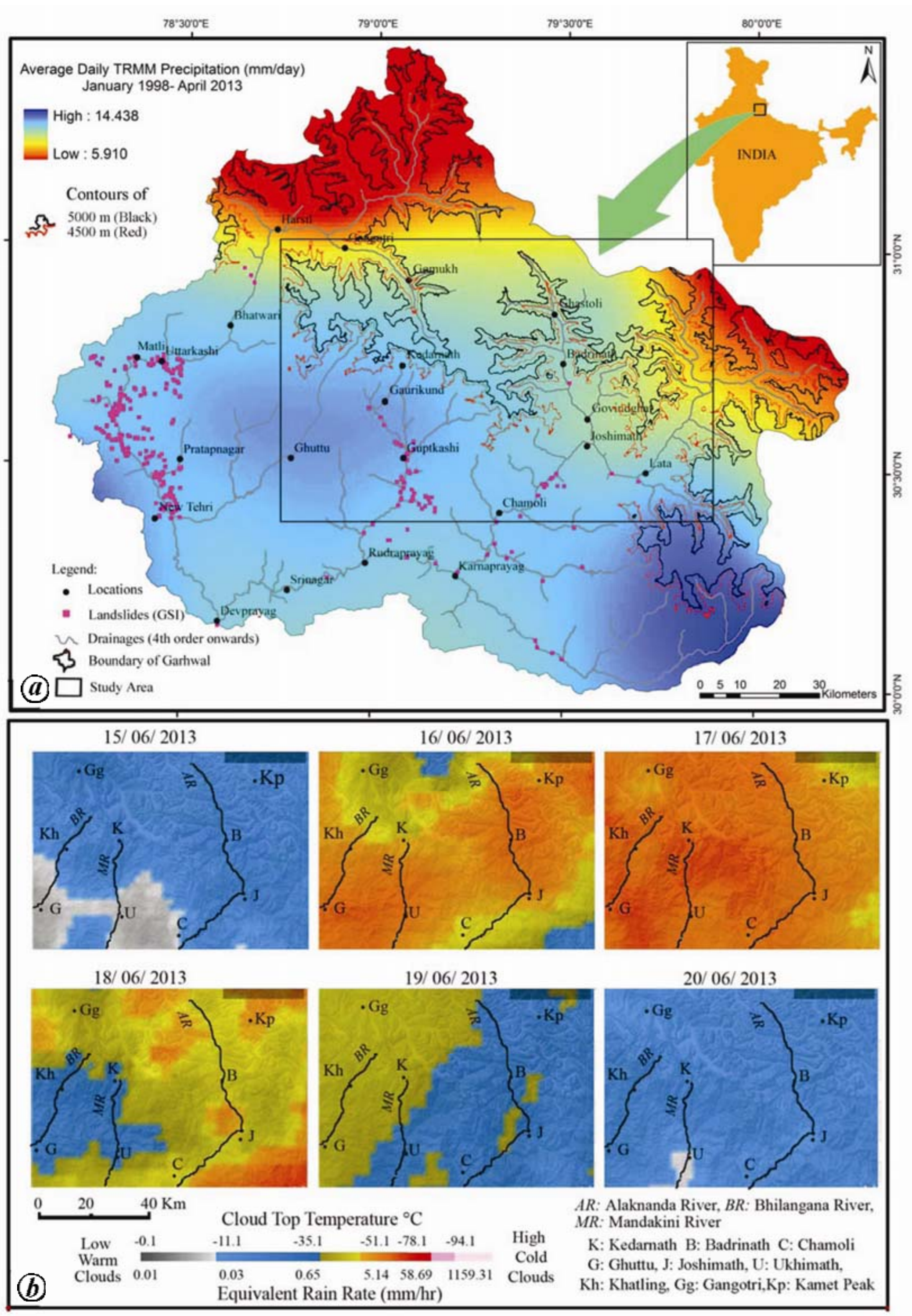

Figure 1. ***a***, Average daily TRMM precipitation (mm/day) data during the period January 1998–April 2013 for Garhwal area. Red areas show regions of low precipitation, and the bluish areas indicate regions of higher precipitation. Majority of landslides (source: GSI dataset) fall in the valley portions of high rainfall. Black box shows the areas affected by extreme rainfall of 16–17 June 2013. ***b***, Daily rainfall from 15 to 20 June 2013 for the affected areas. The very high rainfall during 16 and 17 June resulted in the disaster.

Boundary Thrust (MBT) to the south, which are tectonically very active[12–14]. Both MCT and MBT are suggested to be reactivated and are sometimes referred to as out-of-sequence thrusts (OSTs)[15–18]. These thrusts are structurally controlled and govern the orographic behaviour of the monsoons in the Himalaya[13,19–21].

Hence to study the relation of orography with the extant Himalayan landscape, the Tropical Rainfall Measuring Mission (TRMM) data[22,23] were downloaded for the period 1998–2013 (April) for Garhwal area. The average daily precipitation (mm/day) pattern as shown in Figure 1 *a* indicates that there are two peaks corresponding to high rainfall each in the western and eastern portion of Garhwal Himalaya. The areas of low precipitation are situated in the extreme north of Garhwal region. Thus there exists a boundary which demarcates the areas of high and low precipitation in the Garhwal Himalaya. Moreover, the areas situated in the northern portion are mostly glaciated and snow-covered; hence they are located in higher latitudes and altitudes. The contours of 4500 and 5000 m also follow similar trend in the study area bound by a black box (Figure 1 *a*). Thus a topographic barrier exists which does not allow precipitation to occur in these higher reaches. When the western disturbance increases (as in this case), it intensifies the monsoonal event and causes extreme precipitation. The pattern of western disturbance is clearly visible in the post-monsoon TRMM data, where highest precipitation occurs in the upper reaches. Thus during the monsoon season, the areas of Kedarnath, Badrinath, Joshimath, Bhatwari, etc. lie on the windward side and hence receive more precipitation compared to the areas of the extreme north and those at higher altitudes. The orographic effects in these areas are the major contributing factors which created such devastation. The landslide data from the Geological Survey of India also indicate that the activities like landslides, slumping and sinking of the ground happen in these areas where comparatively higher precipitation occurs (Figure 1 *a*).

Further, in these areas (marked by a box in Figure 1 *a*), the rainfall data were obtained from Geostationary Operational Environmental Satellite (GOES) series of satellites operated by National Oceanic and Atmospheric Administration (NOAA) in and around Kedarnath area during the period 15–20 June 2013. It is evident from Figure 1 *b* that the central portion of the study area, which includes Kedarnath, Ukhimath, Joshimath and Badrinath, is the worst affected. According to IMD, rainfall started on the night of 15 June 2013 and continued for more than two days, breaking an 88-year record for the month of June. It is supported by the satellite image for that night where the precipitation is partially distributed during 00:00–22:00 h of 15 June. After 10 p.m. on 15 June, the precipitation amount increased and rainfall occurred till 6 a.m. on 16 June, averaging approximately 90 mm. Afterwards, the precipitation decreased till 1 p.m. on 16 June. The floodgates were then opened and incessant torrential rains started, which continued till 4 a.m. on 18 June. During this time the total precipitation that occurred in the area was nearly 600 mm in 36 h. Similar observations were made at the WIHG meteorological observatory at Chorabari Glacier camp[1]. During these 36 h the intensity of rainfall decreased during 3–7 a.m. and 1–8 p.m. on 17 June. Yet the amount of rainfall that occurred was sufficient to wipe out the towns and villages downstream. Finally, rainfall stopped after 4 a.m. on 18 June and the aftereffects became visible.

Hence prolonged heavy rainfall for nearly three days over a large area is perhaps unprecedented, and the cumulative effect of various parameters such as geological, tectonic, orographic, meteorological, environmental and anthropogenic factors, is the reason for the enormity of this disaster. Thus it is clear that the orographic barrier at the south of the Higher Himalaya is playing a major role in the climate dynamics of the region. The western disturbance enhances its effect and causes such abnormal rainfall. Thus, the areas that lie to the south of such a barrier are most vulnerable to such hydro-meteorological hazards and their repercussions are beyond imagination.

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