environment over the equatorial plane, some of the CHACE findings are likely to be vindicated. Further, unlike in the case of CHACE, which was a 'one shot' mission, the distinct advantage of LADEE which would be an orbiting spacecraft initially at around 250 km and later coming down as low as 20 km, with an anticipated lifetime of ~ 3 months, is that the whole of the lunar globe is likely to be covered over the equatorial plane. This would clearly bring out the spatial heterogeneity indicated by India's CHACE experiment, in addition to the inferences on the lunar day and night pressure differences.

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ACKNOWLEDGEMENTS. This work is supported by the Department of Space, Government of India. R.S. thanks NASI for the Senior Scientist position and the Director, PRL, Ahmedabad for providing the necessary facilities.

Received 9 October 2013; accepted 11 October 2013

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Lessons from Kedarnath tragedy of Uttarakhand Himalaya, India

The complete destruction by Mandakini River in Kedarnath on 16 and 17 June 2013 could not have been avoided. Yet, the number of casualties would have been far less had the mushrooming growth of hotels, lodges and dharmshalas not been allowed in Kedarnath. This has been one of the worst Himalayan tragedies in recent years in which the exact number of people buried/perished is not known as thousands are still missing. Almost the entire Rambara and a large part of Gaurikund and many villages of Mandakini valley were also wiped out. The flash flood and attendant debris flow was undoubtedly an irrepressible natural hazard. However, its worst impact must be viewed in the perspective of high vulnerability (of this area) mainly attributed to rampant construction activity for commercial purpose in Kedarnath, Rambara and Gaurikund in the close proximity of Mandakini River and also the uncontrolled floating population of pilgrims. It was the worst-case scenario with an area of very high vulnerability (man-made) experiencing flash floods and debris flow induced by torrential rains, Chorabari lake collapse and mobilization of glacial material[1]. This correspondence discusses the measures aimed at reducing the vulnerability of this area in the future.

About 131 years ago in 1882 only the Kedarnath temple and four to five huts (chhan in local parlance) existed in the region.

Some decades ago, the holy shrines of Uttarakhand did not witness heavy influx of floating population of pilgrims and tourists. Also, there was no rampant construction activity on active and old flood plains and lower terraces of rivers and on critical hill slopes. Our rising population, economic growth and improved lodging facilities due to rapid transformation in the livelihood strategies of locals have drastically increased the influx of pilgrims and tourists in this region.

A few years back, the pilgrims used to start their journey from Gaurikund to Kedarnath on foot or by pony early in the morning just to ensure their return to Gaurikund by afternoon on the same day. This was because there were few lodges/hotels in Kedarnath and even far lesser number of such facilities in Rambara, which is a transit point midway between the 14 km long pony route from Gaurikund to Kedarnath.

The area is geodynamically unstable with neotectonic movements and high frequency of landslides, including rock falls, debris flow and ground subsidence[2,3]. The source of the Mandakini River is formed by Chorabari and an unnamed companion glacier. The settlement of Kedarnath is just 500 m below the snout of these glaciers and the terminal moraine hump is about 275 m high from the outwash plain over which Kedarnath is situated (GSI, unpublished). Examination of satellite images indicates that this outwash plain might have been reworked by the Mandakini River in the past and a major part of Kedarnath till 16 June 2013 was located on the old flood plain (T_1 terrace). However, the famous Kedarnath temple constructed on a man-made raised platform seems to be located on a higher terrace of the Mandakini River. The moraine ridges running parallel and subparallel to the upper Mandakini valley are conspicuous in Kedarnath and further downstream up to Garuriya and Ghindurpani. After the flash floods and debris flow of 16 and 17 June 2013 (although flood water of the Mandakini River has receded), it would not be geologically incorrect to say that the completely devastated settlement of Kedarnath today lies on the active flood plain of Mandakini River that may be flooded again in the near or far future in the event of torrential rains and or due to mobilization of glacial material.

Critical slopes on the hillside and flash flood-prone banks on the river side restrict the capacity of the Himalayan shrines of Yamunotri, Gangotri, Kedarnath, Badrinath and a number of habitations such as Gaurikund and Rambara (on the way to Kedarnath) and Janki chatti (on the way to Yamunotri) to safely accommodate the growth of 3–4-storied hotels and lodges.

Rampant construction of commercial facilities such as hotels, restaurants and lodges in close proximity of the Himalayan rivers narrows down the space for these rivers to accommodate their unrelenting spate during high monsoonal rains in their catchment. During the flash floods of June 2013, the narrow Mandakini valley (at many places) seems to have hindered the spread of flood water, which then might have risen to very high level thus wiping out large stretches of the pony route between Gaurikund and Kedarnath even on the middle slopes. Further, many stretches of this pony route are reportedly blocked or damaged by landslides probably triggered due to severe toe erosion by the Mandakini River that might have changed the angle of repose of critical slopes having old slide, colluvial and/or moraine material.

The pre- and post-disaster images released by NRSC[4] indicate that the swollen Mandakini River and attendant debris flow probably comprising moraine material have devastated the constructions even on the middle and upper terraces in Kedarnath. During high floods, the rivers acquire a shorter, straight path similar to the one carved by the flood water of Mandakini River (along with debris and boulders) through the settlement of Kedarnath. On the eastern extremity of Kedarnath the more or less abandoned channel of Saraswati River was also flooded severely. Reconstruction of hotels, lodges, dharamshalas and shops at these sites will again raise the vulnerability of Kedarnath to pre 16 June 2013 level. Constructions on moraine ridges (juxtaposing the moderately steep hill slopes) at Kedarnath will be vulnerable to subsidence as well as landslides. Blanket ban is needed on further construction activity on active flood plains and restricted constructional activity on old flood plains and lower terraces of rivers all along the river valleys of Mandakini, Alaknanda, Bhagirathi, Yamuna and their tributaries and also along other rivers in parts of Uttarakhand.

Cutting down trees to some extent has destroyed the natural barriers against flash floods and debris flow slides along the river banks in hilly regions. The development of ecozones in severe and very high flash flood hazard-prone selective stretches of active and old flood plains of the Himalayan rivers and also in very high to severe landslide hazard-prone areas will drastically restrict the mushrooming growth of multistoried hotels and lodges in these areas. This in turn will restrict the concentration of human population and also anthropogenic intervention in these areas.

The new pony route alignment to Kedarnath should be on the middle and upper hill slopes (that too after detailed geotechnical investigations), since the area is highly prone to landslides[2]. Slope cutting even for construction of pony route may trigger new landslides and activate old slides at some places. Feasibility of rope ways as a safer means of transport in very high to severe flash flood and landslide hazard zones should also be assessed.

Reconstruction of Kedarnath must include structural mitigation measures for flood control, including river training and bank protection work in the immediate upstream of Kedarnath temple in an effort to mitigate to some extent the impact of flash floods in the future. Regular monitoring and credible early warning of prevailing hazard scenario in glaciers and Chorabari lake in the upstream area of Kedarnath are needed[5]. Further, a hospital, police station, accommodation for priests, PCO facility, Temple Committee office and Yatra Management Group office with accommodation for those manning these critical facilities should be constructed with earthquake-resistant design on flood and landslide safe (to some extent) locations in Kedarnath or its vicinity, as the area is prone to multi-hazards. According to the *Vulnerability Atlas of India*[6], this area falls in Earthquake Very High Damage Risk Zone V and also in the high landslide hazard zone[2]. The events of 16 and 17 June 2013 have demonstrated that Kedarnath area is severely prone to flash floods and attendant debris flow as well. Only some basic facilities like day-time retiring halls for pilgrims and locals and a couple of warehouses for stockpiling rations and cooking fuel for emergency purposes should be constructed. This would drastically reduce the vulnerability of the shopkeepers, vendors, hoteliers and floating population of pilgrims and tourists to future flash flood and debris slide events.

A yatra management system for the Char Dham Yatra (pilgrimage to four shrines of Uttarakhand namely Yamunotri, Gangotri, Kedarnath and Badrinath) needs to be put in place. Advance booking system for this yatra should be introduced and only a limited number of pilgrims should be allowed to visit the shrines. Further, a yatra management group also needs to be constituted comprising officials from the Department of Disaster Management, Police and Nodal Officers from the districts falling on the pilgrimage routes and also a representative from India Meteorological Department (IMD). This group should be responsible for necessary decision-making regarding suspending the pilgrimage and immediate evacuation of stranded people in the event of bad weather conditions. There is a dire need for close coordination between IMD and the local authorities. The forecast of very heavy rains in hill regions of Uttarakhand should be a critical input for continuing or discontinuing the Char Dham Yatra. The pilgrimage should be suspended and pilgrims sent back if there is forecast of very heavy rains. This would reduce the vulnerability of floating population of pilgrims to the probable onslaught of flash floods and/or landslides. Once Kedarnath yatra resumes, it should be conducted in batches. One or two flood and landslide-safe locations can be identified midway (on the pony route) for overnight stay. No one should be allowed to stay at Kedarnath in the evening, except the personnel of emergency support functions such as doctors, the police personnel, priests, members of the temple management and yatra management committees, personnel maintaining communication towers and power and drinking water supply. Quick response teams equipped with emergency communication facilities, first-aid kits and rescue equipment should be based at important locations of Char Dham Yatra routes during the yatra season.

It was our mistake during the recent years to commercialize the holy shrine of Kedarnath. Now it would be a blunder on our part to do so again. In the near future we may not have the technology to prevent or even precisely predict the time and area that will be affected by flash flood and debris flow events, but we can drastically reduce the vulnerability of the population of pilgrims, tourists, shopkeepers and locals to such hazards. The big question that remains unanswered is, are we prepared to restrict the Kedarnath type commercialization in other Himalayan, shrine areas, namely Yamunotri and Janki Chatti? Are we ready to pay the price for not commercializing shrines such as Kedarnath and Rambara again?

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ACKNOWLEDGEMENTS. I thank Mr P. N. Shah, Director, Dr T. S. Kachhwaha, Dr A. K. Tangri and Mr Rajiva Mohan, Divisional Heads (RSAC-UP) for useful suggestions. I also thank Dr A. C. Pande, Prof. H. C. Nainwal, Dr S. K. Srivastav, Dr Ajay Naithani, Mr Meghraj and Dr Rajiv Srivastav and Nidhi Uniyal for support.

Received 10 July 2013; revised accepted 8 October 2013

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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 set-up. 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