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Brief Communication: Climate, topographical and meteorological investigation of the 16–17 June 2013 Kedarnath (India) disaster causes

R. Singh[1], D. Siingh[2], S. A. Gokani[1], P. S. Buchunde[2], R. P. Singh[3], and A. K. Singh[3]

[1]KSK Geomagnetic Research Laboratory, Indian Institute of Geomagnetism, Allahabad, India
[2]Indian Institute of Tropical Meteorology, Pune, India
[3]Department of Physics, Banaras Hindu University, Varanasi, India

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Correspondence to: R. Singh (rajeshsing03@gmail.com)

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Abstract

The devastating episode (17–18 June 2013) at Kedarnath (Uttrakhand, India) caused huge loss of lives and physical/material wealth. To understand this catastrophic event, rainfall/convective data and associated climate meteorological parameters are investigated. Low pressure zone with very high cloud cover (60–90 %), and relative humidity (70–100 %) associated with low ($< 4\,\mathrm{m\,s^{-1}}$) wind velocity over Kedarnath region during 15–17 June are observed. The cause of disaster seems to be the heavy and continuous rainfall associated with snow melting and over flooding/collapse of the Chorabari Lake, located upstream. Monsoon advancement was much faster due to the presence of convectively active phase of the Madden Julian Oscillation.

1 Introduction

The present study investigates the climate conditions and meteorological aspects of heavy rainfall leading to the Kedarnath floods in the Uttarakhand state (India) of Himalayan region during 17–18 June 2013. The flash floods which was also later named as Himalayan tsunami caused a catastrophe resulting into numerous loss of human lives, live stocks and destruction to property in the Himalayan region. Uttarakhand region in Himalayas normally experiences heavy rainfall during July and August months of the Indian summer monsoon season, and is normally associated with landslides and related dangers. Heavy rains in the month of June such as that occurred during 16–17 June 2013 were not reported since many decades (Dobhal et al., 2013; Srinivasan, 2013).

Kedarnath (30°44′6.7″ N; 79°4′1″ E; 3583 m above mean sea level), a pilgrimage temple town, is located in the state of Uttarakhand (India) in the central Himalaya. The Kedarnath valley has a total catchment area of $\sim 67\,\mathrm{km^2}$ with Chorabari Lake up the valley (~ 2 km upstream of Kedarnath town) and with the Mandakini and Saraswati rivers flowing through the valley (Fig. 1). The head of the river Manadakini is flanked by

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snow capped peaks. Twenty three percent of area is covered by glaciers (Mehta et al., 2012). Rest of the hilly area is covered by trees and bare land. The Himalayan range contains moraine and is susceptible to landslide and breakage of river coast.

The Chorabari Lake (known as Gandhi Sarovar Lake), located about 2 km upstream of Kedarnath town is approximately 400 m long, 200 m wide and 15–20 m deep (Fig. 1). The sources of water in the lake are snow melting from the surrounding mountain and local rain water. Usually the maximum snow melting is in the month of June and precipitation is maximum in the months of July and August. As a result, water from the lake drains out safely without creating any havoc. The continuous precipitation in the area from 10–17 June 2013 in addition to snow melting filled the lake at a much faster rate. The situation became like a "cloud burst" type event and the lake was rapidly over flooded. In the absence of automatic rain gauge (or hourly measurement of rain) in the area, it could not be ascertained whether cloud burst occurred or not. A cloud burst usually occurs when the amount of precipitation exceeds 100 mm h^{-1}. The bursting of over flooded lake led to its complete drainage within 5–10 min (Dhobal et al., 2013) leading to sudden and complete destruction in its path. The rain water from the surrounding of Mandakini and Saraswati rivers along with debris of landslides and collapse of river banks flooded the entire area from Kedarnath down to Gaurikund town. Gaurikund town is located 16 km downstream and is the commencement point of the trek to the sacred shrine of Kedarnath. The resting point of Rambara is located halfway between Kedarnath and Gaurikund. The additional huge flux of water from the outburst of Chorabari lake completely washed the whole valley from Kedarnath to Gaurikund. This devastation occurred so fast that nothing could be saved.

In this paper, we have investigated the meteorological parameters like, wind velocity, atmospheric pressure, total cloud cover, surface temperature, relative humidity, surface precipitation, surface convective precipitation, cloud top temperature (day/night) for the selected region of Uttarakhand (lat. 28–33° N; long., 76–81° E) with Kedarnath (30°44′6.7″ N; 79°4′1″ E) in the middle of selected area to understand the plausible causes of early and intense rain leading to flash flood which caused devastation in the valley.

2 Data source

The watch and ward staff of the Wadia Institute of Himalayan Geology (WIHG) stationed at the Chorabari Glacier camp recorded 210 mm rainfall in 12 h from 17:00 h IST (Indian Standard Time), 15 June 2013 to 05:00 h IST, 16 June 2013, and 115 mm rainfall from 05:00 to 17:00 IST on 16 June 2013 (Dobhal et al., 2013) leading to 325 mm rainfall in 24 h. IST = UT + 5:30 h. Another observatory at Ghuttu (about 38 km from Kedarnath) measured 58 mm rain on 15 June, 121 mm on 16 June and 93 mm on 17 June 2013.

The daily meteorological parameters such as wind velocity, wind pattern, pressure, total cloud cover, surface temperature, relative humidity, surface precipitation rate, surface convective precipitation rate with 0.5° grid resolution were obtained from Climate Forecast System Reanalysis (CFSR) data developed by NOAA's National Centre for Environmental Prediction (NCEP) for the selected region (lat. 28–33° N; long., 76–81° E) from the source: http://nomadl.ncep.noaa.gov/ncep-data/index.html. The daily cloud top temperature (day/night) was obtained from MODIS (http://gdata1.sci.gsfc.noaa.gov/ncep-data/) and the daily rainfall from TRMM (http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=TRMM_3B42).

3 Observation and discussion

In Fig. 2a, ground based rainfall data (Dobhal et al., 2013; Joseph et al., 2013), satellite measured total rainfall, surface precipitation, convective precipitation rate and cloud top temperature both for day and night hours during 10–20 June 2013 are shown. There was considerable rainfall during 15–17 June, with a maximum on 16 June. Comparing the precipitation rates, it is evident that the convective process is operative during

15–17 June 2013 with a prominence on 16 and 17 June. The variations of cloud top temperature during the day and night hours are indicative of altitude location of clouds. On 15 June, clouds were at relatively high altitude during the night hours as compared to daytime. On 16 June clouds were almost at the same altitude (~ −40 °C) during night and day hours and led to heavy rain. Cloud altitude slowly decreased (cloud top temperature reached to ~ −4 °C) during the night of 17 June. In order to assess the validity of TRMM data, ground based measurements of rainfall data (Dobhal et al., 2013; Joseph et al., 2013) have been compared to satellite data (Fig. 3). The correlation coefficient between the two came out to 0.86 with good significance level.

Cloud development and rainfall depends on meteorological parameters (Williams, 1995, 2004; Siingh et al., 2013, 2014, 2015). Figure 2b shows six hourly variations of wind velocity, pressure, cloud cover (%), surface temperature and relative humidity for the period 10–20 June 2013. Daily mean variation is also shown in each plot. Wind velocity is seen to remain quite low (less than 4 $\mathrm{m\,s^{-1}}$) during 15–16 June 2013. Wind velocity increased to 8.5 $\mathrm{m\,s^{-1}}$ on the evening of 16 June, and then decreased to < 3 $\mathrm{m\,s^{-1}}$ on 17 June. Pressure measurements clearly showed low pressure zone during 16–17 June. Cloud cover was almost 90 % on 16 June. Large amount of cloud cover associated with low pressure zone supports the convergence of South-west Monsoon through westerly disturbance over the region.

The cloud image taken from Kalpana-1 satellite (www.imd.gov.in/section/satmet/dynamic/insat.htm; Dobhal et al., 2013) on 17 June showed the presence of dense cloud over the Himalayas in Uttarakhand, Himachal states of India and Nepal leading to heavy rain. Relative humidity during 15–17 June was quite high, reaching up to 100 % on 16 June. High value of relative humidity, large cloud coverage and low value of wind velocity altogether resulted in huge rainfall for long duration. The daily mean surface temperature decreased and remained almost constant during the period and after the event. Before the event, slow local heating is observed. The orographic conditions (such as high altitude hilly region covered with tree/vegetation) also add to the convective activity. The upslope ascents of the air parcels, sensitive heat flux, and

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passage of convective cloud system may contribute dominantly to the thermodynamic instability.

The data survey of the last several decades shows that the greatest amount of precipitation in Kedarnath area usually occurs during July and August, sometimes also in September due to the convergence of Southwest Monsoon. Barros et al. (2004) studied the relationship of cloud morphology with land form and orography of the Himalayan region and showed that in this region (from 20 to 35° N) smaller but long-lived convective cloud clusters and disorganized short-lived convective systems advance and retreat as the monsoon propagates away from the Bay of Bengal in June and July, and then recedes in August and September. The Himalayan mountain range acts as a physical barrier to the monsoon current and the nearby Tibetan Plateau acts as a major heat source in the summer and heat sink in winter (Das, 1968; Rao, 1976; Qie et al., 2003).

The monsoon activity reached Uttrakhand state of North India in middle June, which is almost about fifteen to twenty days before the usual time. The southwest monsoon reached Kerala (south India) on its typical date (1 June 2013) and spread over southeast Bay of Bengal on the same day. Till 5–6 June the monsoon progressed over India as expected. During the next 10 days the monsoon advancement became much faster. As reported by the Indian Meteorological Department-2013 southwest monsoon end of season report, the pace of advancement had been the fastest in the last 73 years (1941–2013). The formation of cyclonic storm Mahasen (10–16 May 2013) over southeast Bay of Bengal strengthened the low level cross equatorial monsoon flow over south Andaman Sea and adjoining south Bay of Bengal which aided to the advancement of southwest monsoon. The convectively active phase of the Madden–Julian Oscillation and the associated systematic northward propagation of east–west shear zone at the mid tropospheric levels during this period also helped in faster advancement of monsoon and increased rainfall activity.

Joseph et al. (2013) discussed that tropospheric cold temperature anomalies emanating from the Arctic region penetrated to low latitudes over Indian region and interacted with low pressure system which developed over the Bay of Bengal and moved

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inland. The intrusion of cold air in the presence of moist/humid air along with orographic uplift could have triggered intense convection, low convergence resulting in heavy rainfall over the Uttrakhand. In a similar case of extreme rainfall (July–early August 2010), associated with devastating flood in Pakistan (Hong et al., 2011; Wang et al., 2011; Lau and Kim, 2012), Hong et al. (2011) advocated that southward penetration of cold dry air associated with trough east of the blocking induced anomalous low level convergence and upward motion, and provided favourable environment for northward propagation of monsoon surges. Houze et al. (2011) attributed this event to an association with the anomalous propagation of a depression formed over Bay of Bengal.

Kedarnath town is situated on the outwash plane of Chorabari and companion glaciers in the Mandakini River valley. Mandakini and Saraswati rivers encircle this outwash plane and meet near the town (Fig. 1). Overcrowding of people during past few years have caused change in the course of Saraswati river which now flows just behind the Kedarnath town. Houses built at Kedarnath, and at the downstream located Rambara and Gaurikund towns, are on the loosely bound moraine/fluvial deposits, prone to landslides and river cuttings.

May and June climatically suits for pilgrimage and tours to Uttrakhand and hence maximum pilgrims and travellers are usually present in the state, most of them preferring the Kedarnath valley and surrounding area. To provide amenities/facilities to the surplus population, residents from other region of Uttarakhand also migrate to the valley. As a result, the level of population along with supporting animals is enhanced to a much greater extent than usual. The population is over flooded beyond the capacity of the valley. In order to have accommodation, buildings and temporary shelters are built along the banks of river, sometimes making encroachments in the river bed leading to blockage in the flow of river. In fact buildings, roads and developmental activities have disrupted the smooth flow of rivers in Uttrakhand.

Continuous heavy rain in addition to enhanced ice melting over flooded the Chorabari Lake. Water gushed out from lake burst and flooded Saraswati and Mandakini rivers. Both the banks of Mandakini river were washed off causing massive devastation to the

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Kedarnath town and downstream areas. Flooded water and debris from Saraswati river added to this devastation. Many houses along with other civil structures in Kedarnath town, Rambara and Gaurikund were completely washed out. This occurred in the early morning of 17 June 2013. As a result hundreds of people and animals lost their lives in addition to huge damage of property.

4 Conclusion

Meteorological parameters such as wind velocity, pressure, cloud cover, surface temperature, relative humidity and cloud-top temperature were analyzed to understand the heavy rainfall during 15–17 June 2013, which caused unprecedented loss of human life, animals and properties in the Kedarnath region of Uttarkhand, India. Analysis show that cloud cover reached almost 90 % (on 16 June 2013) and wind speed was low ($< 4\,\mathrm{m\,s^{-1}}$). In addition to this, relative humidity reached $\sim 100\,\%$. These factors support convective heavy rainfall which was observed during 15–17 June 2013. The convergence of southwest monsoon trough and westerly disturbances over the region was observed.

Chorabari lake outburst caused by heavy rain and ice melting in the nearby mountains flooded the Mandakini and Saraswati Rivers. As a result, the towns of Kedarnath, Rambara and Gaurikund were completely washed out. Heavy rain and associated landslides are not uncommon in Uttarkhand during monsoon months (July–September). In June 2013, the monsoon advanced by almost a month and coincided with the peak period of pilgrimage and tourism. Consequently much more loss of human life, animals and property occurred.

Author contributions. The concept of the paper was initiated by R. Singh and D. Siingh. The analyses for the paper were collaboratively done by R. Singh, D. Siingh, S. A. Gokani and P. S. Buchunde. R. P. Singh and A. K. Singh contributed to data interpretation, discussion and manuscript preparation. The final manuscript was prepared by R. Singh and D. Siingh, with the contribution from all co-authors.

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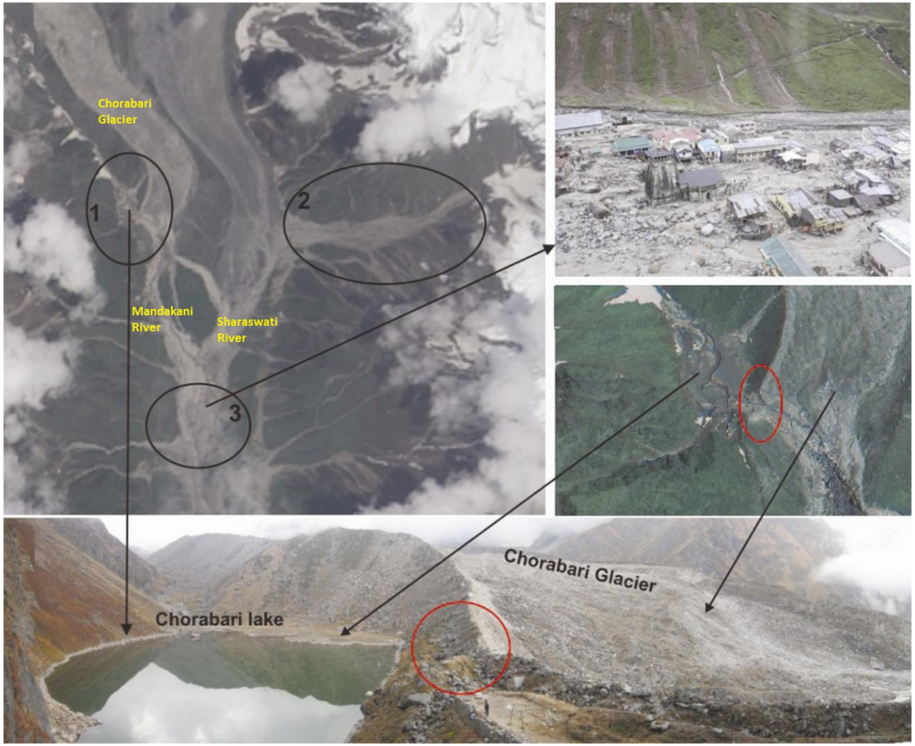

Figure 1. The Landsat satellite image (23 June 2013; after disaster), showing (1) Chorabari lake with Chorabari glacier, Mandakani and Saraswati rivers, (2) gully erosion area in valley and (3) the Kedarnath site of maximum devastation. The red circle indicates the weak zone of the Chorabari Lake, where the lake was burst (modified after Dobhal et al., 2013, Fig. 5).

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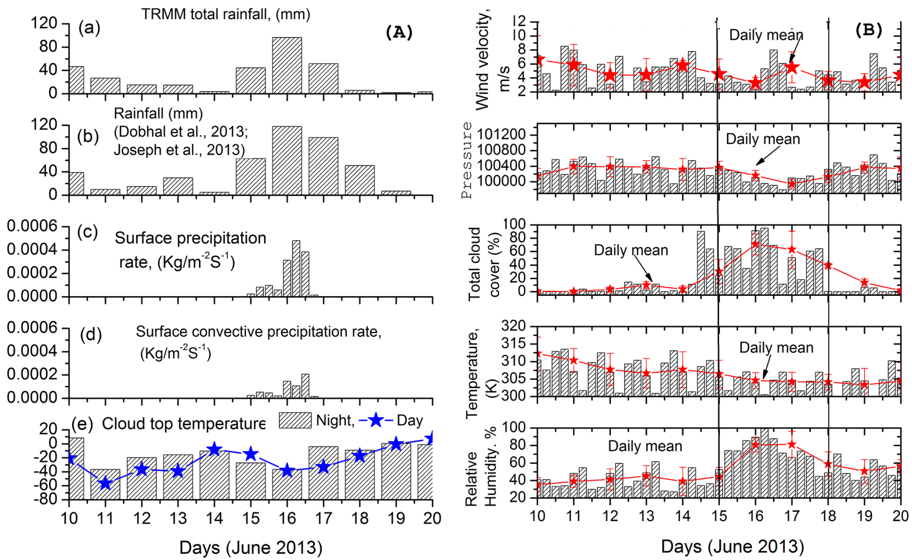

Figure 2. (A) Variation of daily mean **(a)** TRMM total rainfall **(b)** rainfall (Dobhal et al., 2013), **(c)** surface precipitation rate, **(d)** surface convective precipitation rate, and **(e)** cloud top temperature (day/night) for the period 10–20 June 2013. **(B)** Variation of six hourly mean (black line) and daily mean (star and red colour) of meteorological parameters such as wind velocity, atmospheric pressure, total cloud cover percent, surface temperature and relative humidity for the period 10–20 June 2013 for the selected region.

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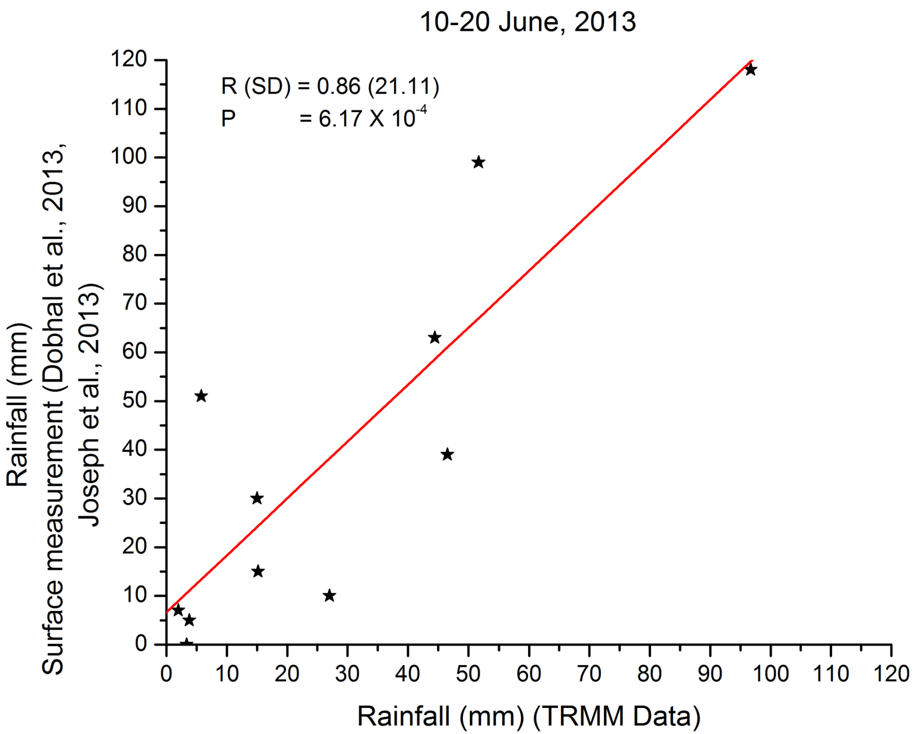

Figure 3. Comparison plot of ground based measured rainfall and TRMM measured rainfall data.

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