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

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Abstract. The devastating flood episode (16–17 June 2013) at Kedarnath (Uttrakhand, India), caused a huge loss of lives and loss of physical/material wealth. To understand this catastrophic event, rainfall/convective data and associated climate meteorological parameters are investigated. A 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, are observed over the Kedarnath region during 15–17 June. The cause of this disaster seems to be heavy and continuous rainfall, associated with snowmelt and the overflooding/collapse of Chorabari Lake, located upstream. Monsoon advancement was much faster than usual, due to the presence of the convectively active phase of the Madden–Julian oscillation.

1 Introduction

The Southwest (SW) monsoon of 2013 over the Indian region (Fig. 1) was very unique in terms of the time of its onset, and its rapid advancement (IMD, 2013). The present study investigates the climate conditions and meteorological aspects of heavy rainfall leading to the Kedarnath floods in the Uttarakhand state (India) of the Himalayan region during 16–17 June 2013. The flash floods were later also named "the Himalayan tsunami" as they caused a catastrophe which resulted in numerous losses of human lives and livestock, and the destruction of property in the Himalayan region. The Uttarakhand region in the Himalayas normally experiences heavy rainfall during the July and August months of the Indian summer monsoon season, and is normally associated with landslides and flash floods. Such heavy rains in the month of June, such as that which occurred during 16–17 June 2013, had not been reported for many decades (Dobhal et al., 2013; Srinivasan, 2013; IMD, 2013). Heavy rainfall was also experienced over parts of Himachal Pradesh, Haryana, Delhi, Uttar Pradesh and parts of the Indian and Nepalese Himalayas. In the current decade, extreme rainfall events leading to flash floods with loss of numerous lives and property have become very frequent in the Indian subcontinent (Hong et al., 2011).

The months of May and June are climatically suited to pilgrimage and tours to Uttarakhnad; hence maximum pilgrims and travelers 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 regions 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 overflooded beyond the capacity of the valley. In order to provide accommodation, buildings and temporary shelters are built along the banks of river, sometimes encroaching on the river bed, leading to a blockage in the flow of the river. In fact, buildings, roads and developmental activities have generally disrupted the smooth flow of rivers in Uttrakhand.

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). The sources of water in the lake are snowmelt from the surrounding mountains and local rainwater. Usually, snowmelt is at

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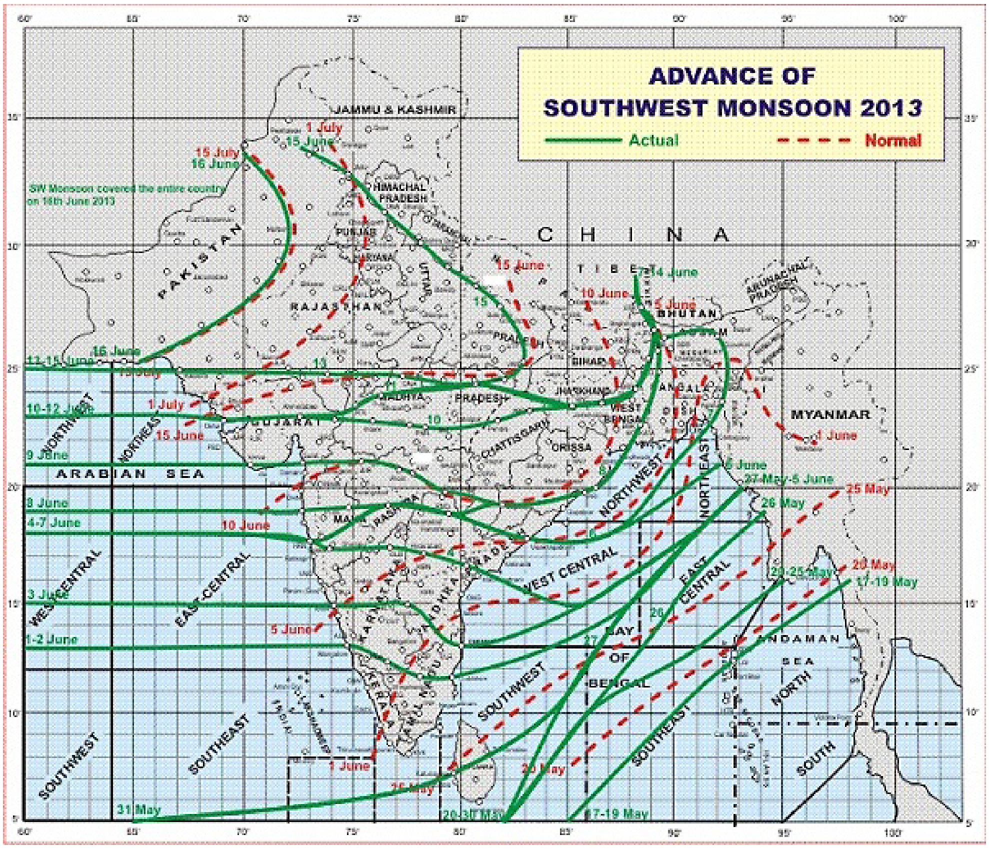

Figure 1. Progress of 2013 Indian Southwest monsoon (Source: http://www.imdpune.gov.in/mons_monitor/mm_index.html).

a maximum in the month of June and precipitation is at a maximum in the months of July and August. Continuous heavy rain during 10–17 June 2013, in addition to enhanced ice melt, overflooded Chorabari Lake in 3 days (Dobhal et al., 2013). Water gushed out as the lake burst and flooded Saraswati and Mandakini rivers. Both the banks of Mandakini River were washed away, causing massive devastation to 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, Rambara and Gaurikund, were completely washed away. 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 to property.

Dobhal et al. (2013) and Joseph et al. (2013) reported on the rapid advance of the 2013 SW monsoon and the concurrent occurrence of the extreme rainfall event in Uttarakhand. Joseph et al. (2013) suggested that during 14–17 June 2013, tropospheric cold temperature anomalies emanated from the Arctic region, penetrated down the latitudes and moved towards the Indian region. However, the India Meteorological Department (IMD, 2013) suggested that heavy to very heavy rainfall during this period, due to the convergence of the Southwest monsoon trough and westerly disturbances, led to the formation of dense cloud over the Uttarakhand. In this Communication, we have investigated the meteorological parameters like wind velocity, atmospheric pressure, total cloud cover, surface temperature, relative humidity, surface precipitation, surface convective precipitation and cloud-top temperature (day/night) for the selected region of Uttarakhand (28–33° N, 76–81° E), with Kedarnath (30°44′6.7″ N, 79°04′01″ E) in the middle of the selected area, to understand the plausible causes of early and intense rain which led to flash floods which caused devastation in the valley.

2 Site description and data sources

Kedarnath (30°44′6.7″ N, 79°04′01″ E; 3583 m above mean sea level), a pilgrimage temple town, is located in the state of Uttarakhand (India) in the central Himalayas. The Kedarnath valley has a total catchment area of ∼ 67 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. Twenty three percent of the area is covered by glaciers (Mehta et al., 2012). The rest of the hilly area is covered by various species of trees such as chir pine, oak, birch and rhododendrons, and covered by alpine meadows and bare land. The Himalayan range contains moraine and is therefore susceptible to landslides as well as the river coast being susceptible to breakage.

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

3 Observations and discussion

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) on 15 June 2013 to 05:00 h IST on 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 is calculated by UT+05:30 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 continuous precipitation in the area from 10–17 June 2013 in addition to snowmelt filled the lake at a much faster rate than usual. The situation became like a "cloudburst"-type event and the lake was rapidly overflooded. In the absence of an automatic rain gauge (or hourly measurements of rain) in the area, it could not be ascertained whether a cloudburst occurred or not (a cloudburst usually occurs when the amount of precipitation exceeds 100 mm h^{-1}). The bursting of the overflooded lake led to its complete drainage within 5–10 min (Dhobal et al., 2013), leading to sudden and complete destruction in its path. The rainwater from the surroundings of Mandakini and Saraswati rivers, along with debris of landslides and collapse of river banks, flooded the entire area from Kedarnath town 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 washed the whole valley from Kedarnath to Gaurikund completely away. This devastation occurred so fast that nothing could be saved.

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 are shown, for both day and night hours during 10–20 June 2013. The cloud-top temperature is the measure of altitude which decreases with altitude. There was considerable rainfall during 15–17 June, with a maximum on 16 June. The heating of the Earth's surface and adjacent boundary layer by the incident solar radiation causes thermodynamic instability of the boundary layer and helps the formation of thunderstorms and rain. The surface temperature and its vertical gradient control the development and intensity of convection, which affects precipitation. In general, studies showed that weak and moderate convection is required for the precipitation (Siingh et al., 2015 with references therein). 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 in 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 night hours as compared to daytime. On 16 June clouds were almost at the same altitude (~ -40 °C) during night and day hours; this led to heavy rain. Cloud altitude slowly decreased (cloud-top temperature reached $\sim - 4$ °C) during the night of 17 June.

Cloud development and rainfall depends on meteorological parameters (Williams, 1995, 2004; Siingh et al., 2013, 2014). Figure 2b shows 6 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 ms^{-1}) during 15–16 June 2013. Wind velocity increased to 8.5 ms^{-1} on the evening of 16 June, and then decreased to < 3 ms^{-1} on 17 June. Pressure measurements clearly showed a low-pressure zone during 16–17 June. Cloud cover was almost 90 % on 16 June. A large amount of cloud cover associated with a low-pressure zone supports the convergence of the Southwest monsoon through westerly disturbance over the region.

The cloud image taken from the 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 and 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. A high value of relative humidity, large cloud coverage and a low value of wind velocity altogether resulted in huge rainfall for a 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 trees/vegetation) also add to the convective activity. The upslope ascents of the air parcels, sensitive heat flux and the passage of the 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 the Kedarnath area usually occurs during July and August, and sometimes also in September due to the convergence of the Southwest mon-

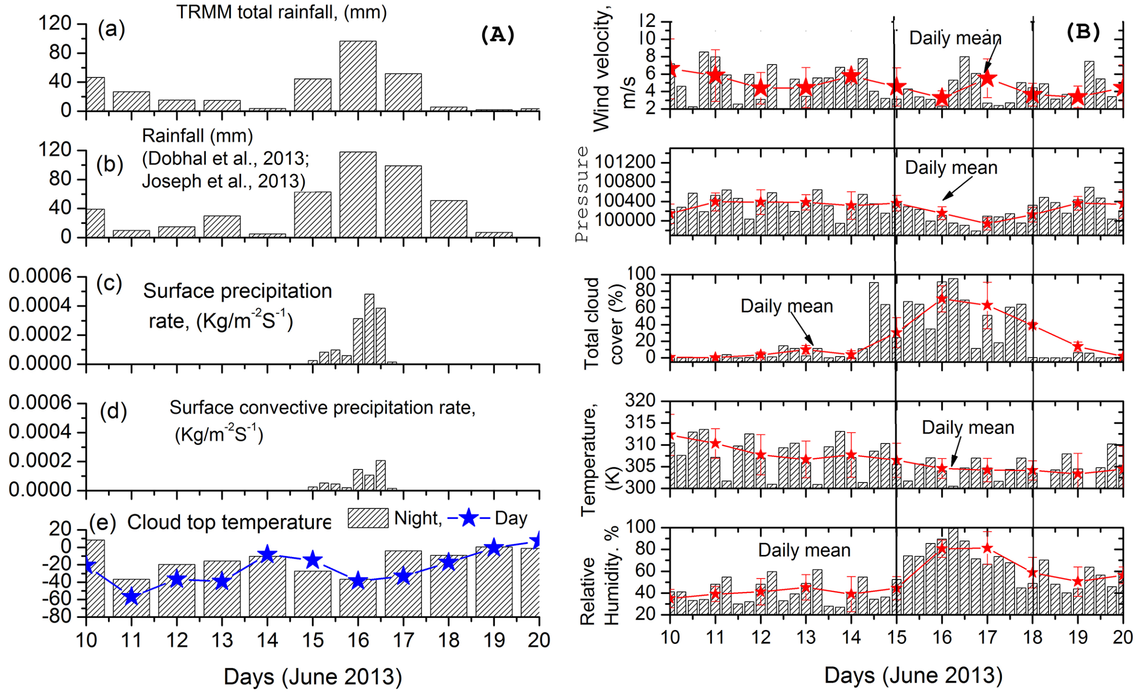

Figure 2. (a) Variation of daily mean **(a)** TRMM total rainfall **(b)** rainfall (Dobhal et al., 2013), **(c)** surface precipitation rate, **(d)** surface convective precipitation rate, and **(e)** cloud-top temperature (day/night) for the period 10–20 June 2013. **(b)** Variation of 6 hourly mean (black line) and daily mean (stars, in red) of meteorological parameters such as wind velocity, atmospheric pressure, total cloud cover percentage, surface temperature and relative humidity for the period 10–20 June 2013 for the selected region.

soon. 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 the 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 15 to 20 days before the usual time. The Southwest monsoon reached Kerala (south India) on its typical date (1 June 2013) and spread over the southeast of the Bay of Bengal on the same day. Till 5-6 June the monsoon progressed over India as expected. During the following 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 the southeast of the Bay of Bengal strengthened the low-level cross-equatorial monsoon flow over south Andaman Sea and adjoining the south of the Bay of Bengal, which aided the advancement of the 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 the faster advancement of the 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 the Indian region and interacted with a low-pressure system which had developed over the Bay of Bengal and moved inland. The intrusion of cold air in the presence of moist/humid air along with orographic uplift could have triggered intense convection and low convergence, resulting in heavy rainfall over the Uttrakhand state. In a similar case of extreme rainfall (July–early August, 2010), associated with devastating floods 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 the trough east of the blocking of air masses, induced anomalous low-level convergence and upward motion and provided a favorable environment for the northward propagation of monsoon surges. Houze et al. (2011) attributed this event to an association with the anomalous propagation of a depression formed over the Bay of Bengal.

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 shows that cloud cover reached almost 90 % (on 16 June 2013) and wind speed was low ($< 4\,\mathrm{ms}^{-1}$). In addition to this, relative humidity reached ~ 100 %. These factors support convective heavy rainfall which was observed during 15–17 June 2013. The convergence of the Southwest monsoon trough and westerly disturbances over the region was observed. The monsoon advanced by almost a month and coincided with the peak period of pilgrimage and tourism in June 2013. Due to heavy rain and ice melt from the nearby mountains, much loss of human life, animals and property occurred.

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

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