Did a cloud burst occur in Kedarnath during 16 and 17 June 2013?

In recent decades many parts of India have experienced frequent flood events[1]. A multi-day extreme rainfall event occurred during 15–17 June 2013 in Uttarakhand that caused devastating floods. The heavy rains resulted in massive landslides and huge destruction of life and property. Rain gauges and radars are conventional tools used to monitor heavy-rainfall events. An accurate measurement of rainfall can be made if there is a dense and homogeneous network of rain gauges over a region. Unfortunately, over Uttarakhand and some other parts of the India, such a network is not available. Radar observation of such events is not easy in a region with complex topography like Uttarakhand. Thus satellite monitoring of rainfall is the only available tool for monitoring these events. During extreme rainfall events there is a large spatial and temporal variation of rainfall and hence hourly satellite data are required to assess the impact of heavy rainfall. Microwave observations from the satellite provide a direct measurement of rainfall, but they do not have sufficient temporal sampling over Uttarakhand. The Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) has insufficient passes over the Kedarnath region during the heavy rainfall event. There was no pass of PR during 16 June 2013 over the affected area. There were just two passes of PR from 15–17 June over Uttarakhand (Figure 1).

Thus data from TRMM PR are not adequate to explore the temporal and spatial variation of rainfall in this region. In this study, we have used hourly observations from Meteosat-7 geostationary satellite data to monitor the extreme rainfall event over Kedarnath (30.7–30.8°N, 79–79.1°E). The indirect estimate of rainfall from infrared (IR) radiance may reveal if there was a strong diurnal variation of rainfall over this region. We have adopted the rain index-based technique developed by Mishra[2] to estimate rainfall from Meteosat IR and water vapour (WV) channels at 5 km resolution. A multispectral method was used to develop the rain index. Colder clouds in IR images are more likely to precipitate than warm clouds because cold (deep) clouds have higher cloud tops than warm clouds. Wu and Weinmann[3] have shown that measurements in water vapour absorption channel are highly sensitive to the ice concentration in the upper portion of the clouds and convective rainfall rate. Water vapour imagery can be used to detect dry and moist regions. Within a dry region, precipitation intensity diminishes and precipitation chances are reduced, whereas within the moist region precipitation chances are increased. For the development of the IR and WV rain coefficients, brightness temperature in these channels (TB_{IR} and TB_{WV}) was collocated with surface rain observations from the PR. From this relation, non-rainy TB thresholds at IR and WV channels (denoted as TB_{IR0} and TB_{WV0}, respectively) were estimated as 300 and 250 K respectively. IR rain coefficients are defined as

$$IR_{index} = TB_{IR0}/TB_{IR}. \tag{1}$$

If $TB_{IR} \geq 300$, then $IR_{index} \leq 1$, and it indicates a non-rainy condition.

Similarly, WV rain coefficients can be defined as

$$WV_{index} = TB_{WV0}/TB_{WV}. \tag{2}$$

If $TB_{WV} \geq 250$, then $WV_{index} \leq 1$, and it is an indicator of non-rainy condition.

Finally, rain index (RI) is defined as

$$RI = IR_{index} \times WV_{index}. \tag{3}$$

If $TB_{IR} \geq 300$ and $TB_{WV} \geq 250$, then $RI \leq 1$, and it indicates a non-rainy condition. Smaller values of TB_{IR} and TB_{WV} are associated with very high values of RI (deep convective systems with very heavy rainfall).

These rain indices were collocated against the rainfall rate from PR to establish a relationship between the rainfall from PR and rain indices from Meteosat.

$$\text{Rain rate (mm/h)} = \alpha + (\beta \times RI^{\gamma}), \tag{4}$$

where $\alpha = -8.4969$, $\beta = 2.7362$ and $\gamma = 4.27$. A value of RI above 1.8 indicates very heavy rain event (associated with very deep convective clouds).

Validation with rain gauges and PR suggests that rain index-based technique is efficient enough to study heavy precipitation events at very fine scale over the Indian region[2]. This rain index-based technique has been used to study heavy rainfall events over Kedarnath during 15–17 June 2013.

Hourly rainfall was estimated from Meteosat data using eq. (4). We have

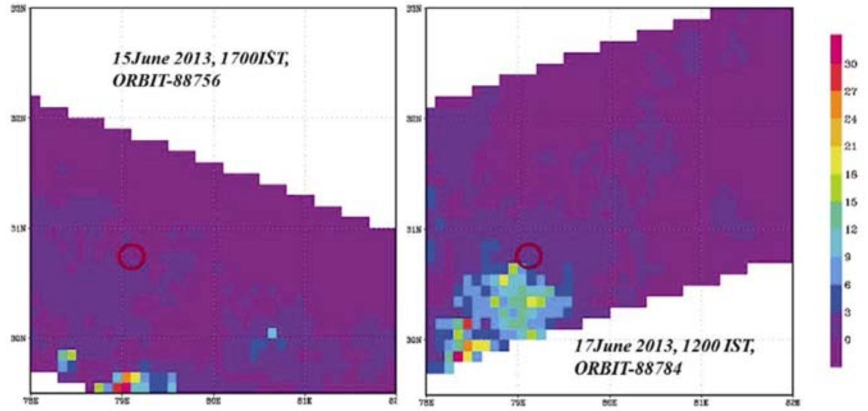

Figure 1. Passes of Precipitation Radar over Uttarakhand region. Red circle represents the Kedarnath region.

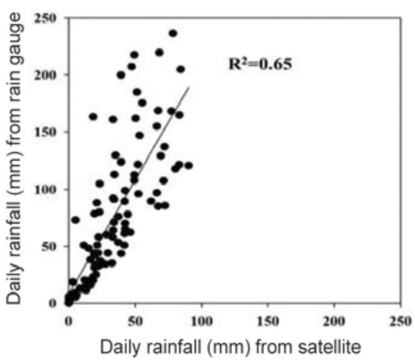

Figure 2. Comparison of rainfall estimated from satellite radiance with daily rain gauge observations from IMD over Uttarakhand during 15–17 June 2013.

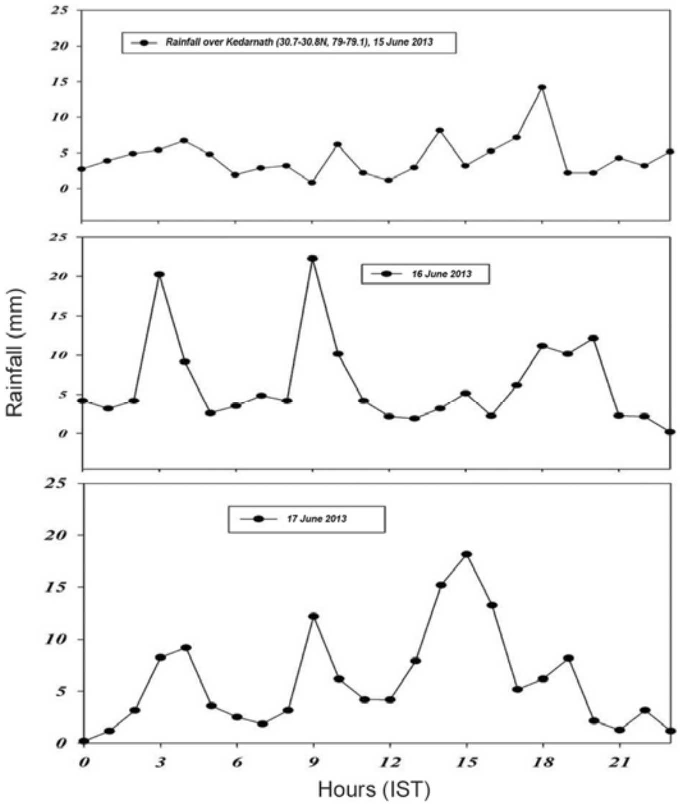

Figure 3. Diurnal variation of rainfall during 15–17 June 2013 over Kedarnath region.

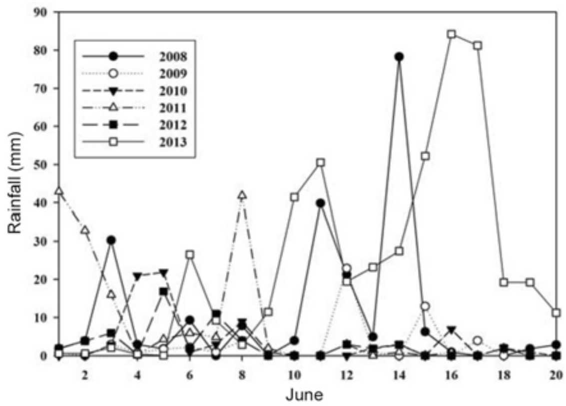

Figure 4. Variation of June rainfall during 2008–2013.

checked the utility of this technique to monitor the heavy precipitation by comparing the daily cumulated rainfall with available rain gauge observations from India Meteorological Department (IMD) over Kedarnath and surrounding regions during 15–17 June 2013. We find that the present technique correlates well with rain gauge observations (Figure 2).

The underestimation of rainfall by satellite may be attributed to the fact that rain gauge represents point measurement of rainfall, while the satellite radiance data are averaged over 5 km by 5 km grid.

Figure 3 shows rainfall over Kedarnath during 15–17 June 2013. It may be observed from the figure that there is a strong diurnal variation of rainfall. There was a peak rainfall of about 15 mm/h on 15 June at 1800 IST. There were two more heavy rainfall activities at 1000 and 1400 IST with rainfall around 7–10 mm/h. On 16 June 2013, two heavy rainfall events (rainfall exceeding 20 mm/h) were observed at 0300 and 1000 IST. A maximum rainfall of about 18 mm/h was observed at 1500 IST on 17 June 2013. So maximum rainfall never exceeded 23 mm/h and hence the possibility of a cloud burst is ruled out. It may be observed that there was no heavy rainfall event preceding the catastrophic debris slide in Kedarnath on 17 June 2013 at 6.45 am. So, it must be concluded that the debris slide was not triggered by concurrent heavy rainfall, but a landslide that led to the bursting of the lake upstream of Kedarnath, as suggested by Dobhal *et al.*[4]. It may be seen that PR records a rainfall of about 3–6 mm/h (Figure 1) over Kedarnath on 17 June 2013 during 1200 IST, which is comparable with the rainfall amount of 5 mm/h obtained using the present technique (Figure 3).

We have compared the daily rainfall in Kedarnath during June 2013 with daily rainfall in June in the preceding five years (Figure 4). It is observed that rainfall during June for 2009–2012 was low and moderate compared to 2013. We find that in June 2008, daily rainfall over Kedarnath was as high as in June 2013, but the cumulative rainfall between 10 and 17 June 2013 was much higher than in the same period in June 2008. This suggests that higher cumulative rainfall in June 2013 may have a great impact on landslides and bursting of the lake upstream of the Kedarnath temple on 16–17 June 2013. Maximum rainfall never exceeded 25 mm/h during 16–17 June 2013. Hence high cumulative rainfall may be more important than a cloud burst to trigger the catastrophic lake burst.

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