

# Catastrophic heavy rainfall episode over Uttarakhand during 16–18 June 2013 – observational aspects

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**Widespread very heavy to extremely heavy rainfall occurred over Uttarakhand and its neighbouring states during 16–18 June 2013, which caused flash floods, landslides, large-scale loss of lives and damage to property. The present study analyses the dynamical and thermodynamical features associated with this torrential rainfall episode. The analysis suggests that due to strong interaction between an oncoming mid-tropospheric trough in the westerlies and the strong lower-tropospheric southeasterly monsoon wind flow in association with a monsoon low-pressure system over the North Indian region, a lower tropospheric wind convergence zone developed over Uttarakhand and its neighbouring regions. A strong Bay of Bengal current of air with wind speed of 40 kts in the northern periphery of the monsoon low, pumped a lot of moisture into the region. Supported by strong orographic effect due to high terrain and strong moisture feeding from both the Arabian Sea and the Bay of Bengal, a large-scale quasistationary regenerative mesoscale convective system (MCS) developed over the zone of convergence. The episode was comparable to the 2010 Leh flash flood episode, in that the synoptic conditions were similar in both cases. However, while the Leh episode resulted from repeated surges of westward travelling MCS across the Tibetan Plateau, the present case was due to quasistationary regenerative MCS over the region.**

**Keywords:** Heavy rainfall episode, mesoscale convective system, synoptic features, thermodynamic features.

UTTARAKHAND (formerly Uttaranchal) is a state in the northern part of India, located in the Western Himalayas. The region is renowned for its natural beauty, as well as pilgrimage sites which dot the upper reaches of the hills. Non-availability of abundant farmland makes the local people mostly dependent on seasonal activities such as tourism for their livelihood. A major group of pilgrimage sites are located in the Uttarkashi and Rudraprayag districts of Uttarakhand. These include the Kedarnath and Badrinath temples, which are holy to the Hindus and

Hemkunt Sahib which is holy to the Sikhs. Together, these pilgrimage sites account for footfalls of tens of thousands of pilgrims from all over India each day during the summer season prior to the onset of monsoon over this region in July. Figure 1 displays the state map of Uttarakhand and its districts.

During 2013, the monsoon pulse travelled northward across the Indian subcontinent much faster than the other years, and monsoon onset took place over the region almost a month in advance of its normal date (15 June instead of 15 July). In association with the early monsoon onset, during the peak summer tourist and pilgrimage season, heavy to extremely heavy rainfall was reported all over the state during 16–18 June 2013. This caused flash floods in the tributaries in the upper catchments of the Ganga and Yamuna rivers over this region, resulting in widespread loss of human life and property. The network of rain gauges of India Meteorological Department (IMD) and the Uttarakhand government, numerical models and remote observation sources such as satellites and radars captured this widespread heavy rainfall episode. The purpose of the present study is to understand the nature of the weather systems that caused such a heavy rainfall episode over this region.

Studies<sup>1</sup> have reported that there has been a substantial increase in the frequency of extreme weather events over the Western Himalayas in the last 30–40 years (International Disaster Database; <http://www.emdat.be>), which may be ascribed to the increase in intensity of the global monsoon accompanying the last three decades of general global warming<sup>2</sup>. The forecasting of heavy rainfall, particularly over high complex terrain, is one of the most challenging tasks for forecasters. This is due to issues which involve the impact of complex orography, lack of understanding of interactions between synoptic scale and mesoscale weather systems, sparse good-quality data over remote areas and large spatial and temporal variations of rainfall. Terrain and multiple-scale interactions<sup>3</sup> are major factors in generating extreme precipitation events. While analysing the rainfall initiation over North India during the pre-monsoon season, studies<sup>4</sup> have noted the strong interaction of mesoscale factors such as orography and synoptic-scale factors (westerly troughs and ridges) that cause an early morning maximum in rainfall initiation

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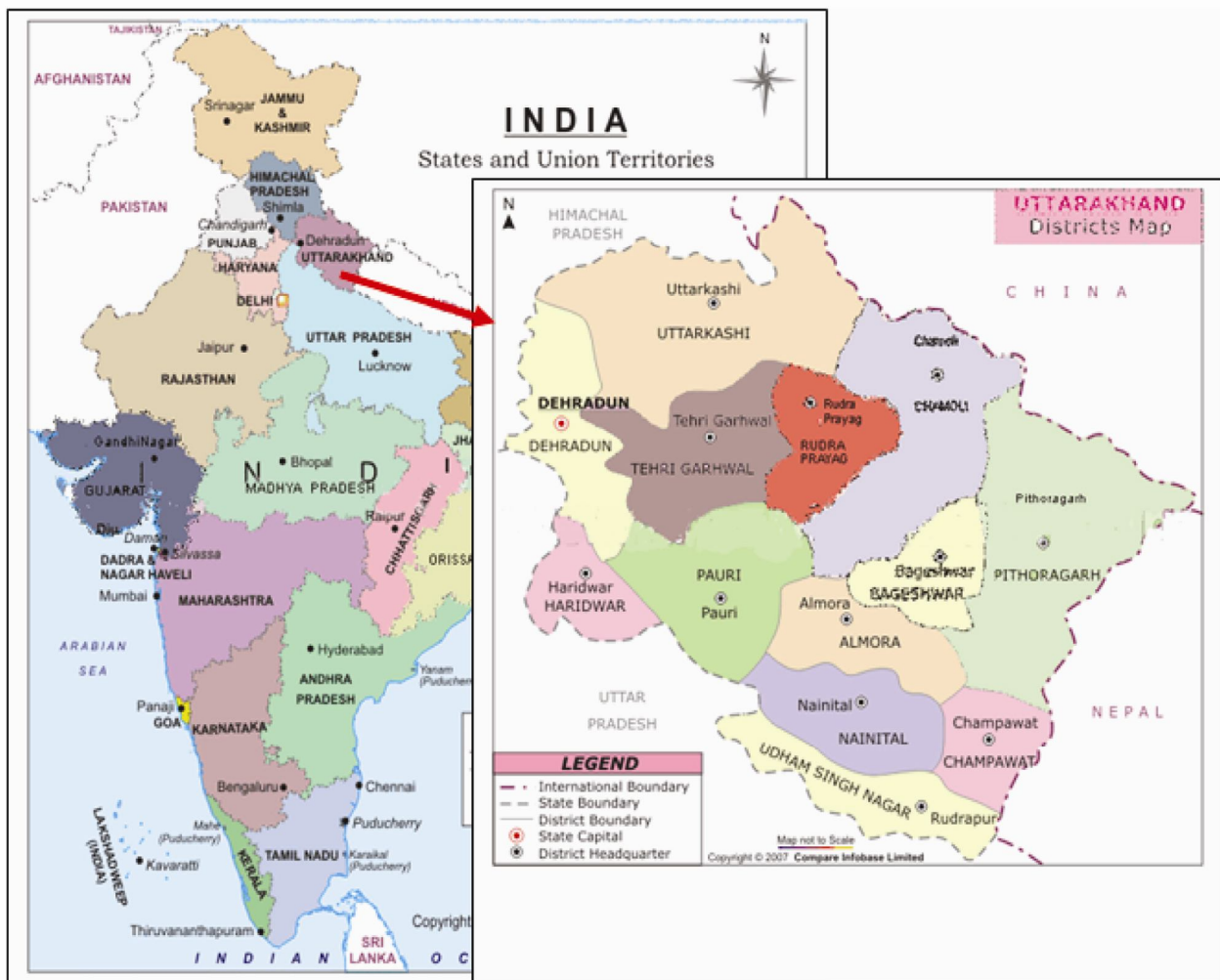


Figure 1. Map of India and the state of Uttarakhand.

in the foothills of the Himalayas. A detailed analysis of a heavy rainfall episode over Pakistan and the Western Himalayas noted that such rainfall episodes are triggered by the anomalous propagation of the Bay of Bengal (BoB) depressions and their moist environment across the subcontinent, along the monsoon trough, to Pakistan<sup>5</sup>. The high-pressure zone over the Tibetan Plateau not only favours the formation of a synoptic-scale channel of anomalously moist flow toward the mountain barrier, but also forms an environment in which the precipitating mesoscale cloud systems take on a form that includes broad stratiform rain regions lying over the slopes of the Himalayas<sup>5</sup>.

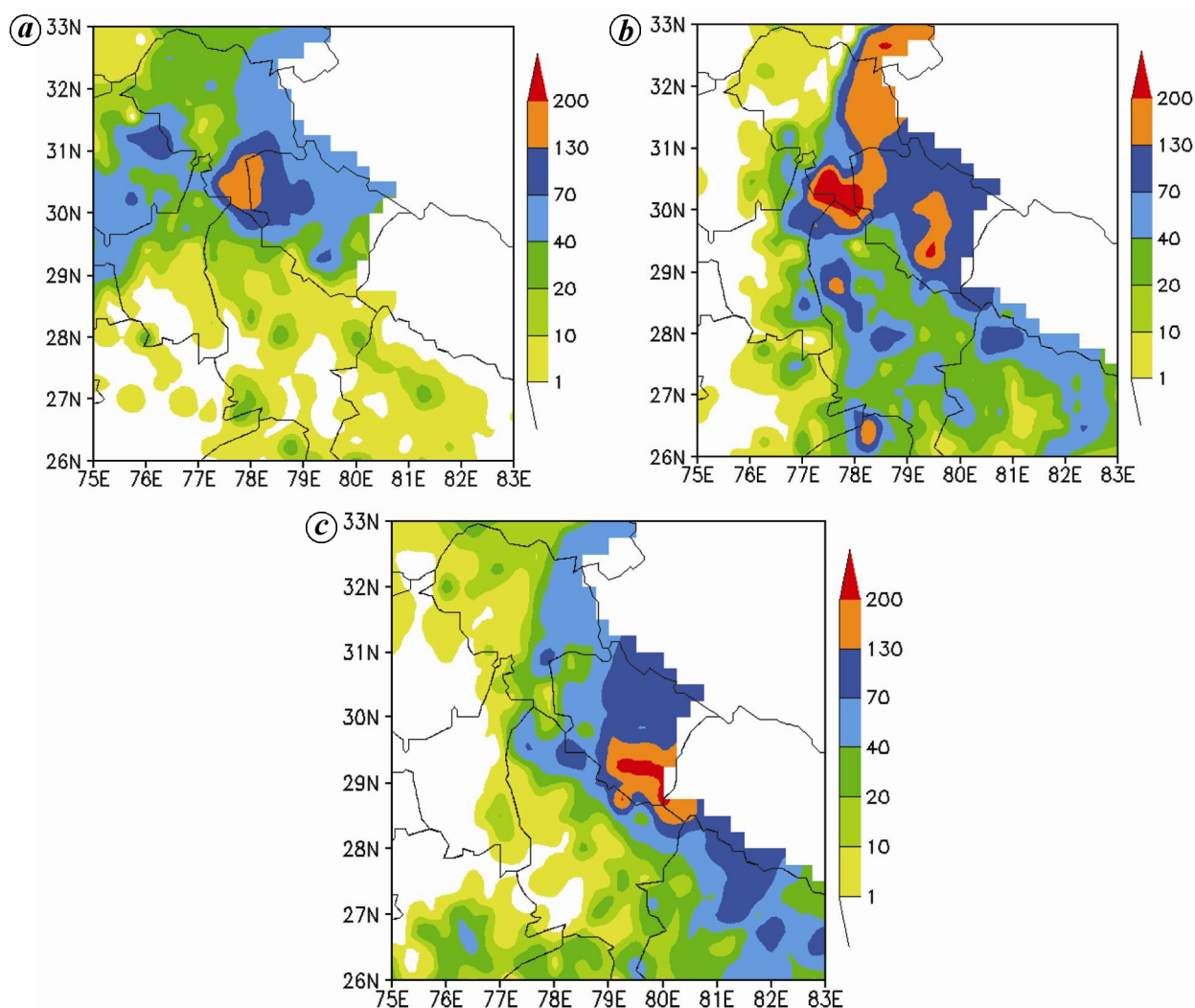
### Data used

The various dynamical and thermodynamical parameters, which are analysed for the heavy rainfall event, are derived from the IMD operational WRF model (27 km resolution) daily analysis fields. Conventional data at

synoptic hours, available on the Global Telecommunication System (GTS) from surface and upper air observing stations from all over the world, and enormous amounts of non-conventional data such as geostationary and polar orbiting satellite radiance and wind data are input into the model to create a suitable initial field for analysis, and generate secondary model products as well as forecasting. For the analysis of the rainfall field, we have considered the high-resolution ( $0.25^\circ \times 0.25^\circ$  lat./long.) gridded daily rainfall dataset for the Indian region<sup>6</sup> created out of a total of 6955 daily reporting stations of IMD. For accurate analysis of the cloud structure and distribution, the observations of the Doppler radar network of IMD are used for analysis.

### Observed rainfall

The spatial distribution of daily  $0.25^\circ$  gridded rainfall<sup>6</sup>, associated with this weather phenomenon during 16–18 June 2013 is shown in Figure 2 *a–c* respectively. A heavy



**Figure 2.** Spatial distribution (resolution  $0.25^\circ \times 0.25^\circ$ ) of rainfall (mm) activity during 16–18 June 2013: *a*, 16 June; *b*, 17 June; *c*, 18 June 2013.

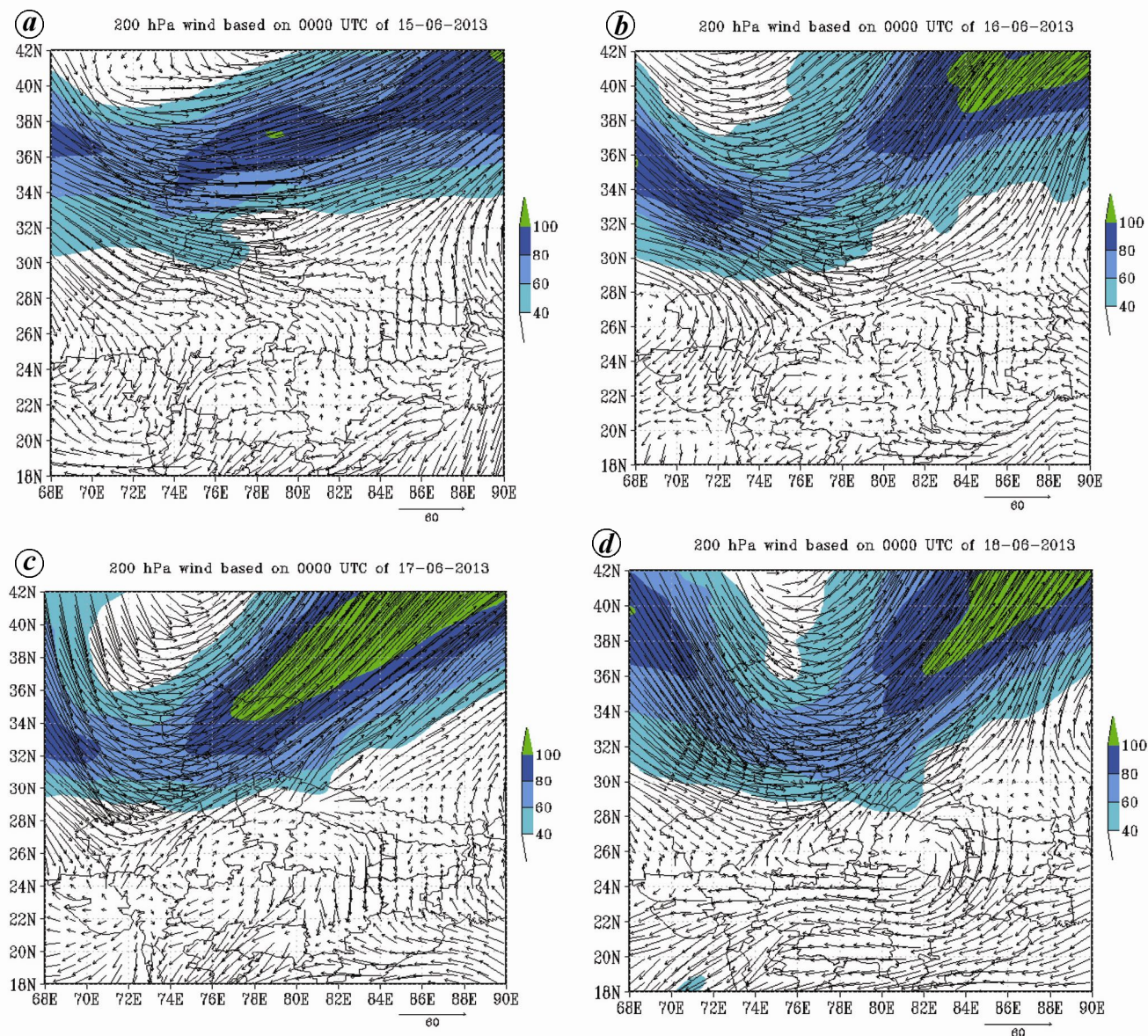
(>6.5 cm) to very heavy (>12.5 cm) rainfall zone was located over Himachal Pradesh (HP), Delhi and Haryana and Punjab. Widespread very heavy rainfall activity was reported at many stations over Uttarakhand and at some stations over HP, Delhi and Haryana and Punjab (Figure 3) with a few stations reporting extremely heavy rainfall (more than 24.5 cm). Heavy rainfall amounts were also reported at some stations over Himachal Pradesh, Delhi and Haryana and Punjab during 16–18 June 2013 (Figure 3). The analysis of district-wise rainfall distribution indicates that heavy to extremely heavy rainfall ( $\geq 10$  cm) occurred on 16 and 17 June 2013 over the western districts of Uttarakhand (Uttarkashi, Dehradun, Haridwar, Teri, Rudraprayag and Pauri) with maximum rainfall of 37 cm reported on 17 June at Dehradun. Thereafter, the heavy rainfall belt gradually shifted eastwards across Uttarakhand. Heavy to extremely heavy rainfall was reported on 17 and 18 June 2013 over the districts in the eastern parts of Uttarakhand (Almora, Nainital, Udham Singh Nagar,

Champawat, Bageshwar, Pithoragarh and Chamoli) with maximum rainfall of 28 cm reported on 18 June at Haldwani of Nainital district.

### Synoptic conditions and thermodynamical features

The wind field and thermodynamic parameters of the WRF model daily analysis fields are used to analyse the synoptic conditions that led to this catastrophic rain event. Wind analysis at 200 hPa (Figure 4 *a–d*) displays the day-to-day evolution of the jet stream core during 15–18 June 2013. The figure shows a gradual deepening of a westerly trough over the North Indian region, which then starts to move away to the east on 18 June 2013. The jet core develops two maxima (>60 kt shaded with blue and green colour) over the Indian region. The region ahead of the western jet core (right exit sector), which coincides

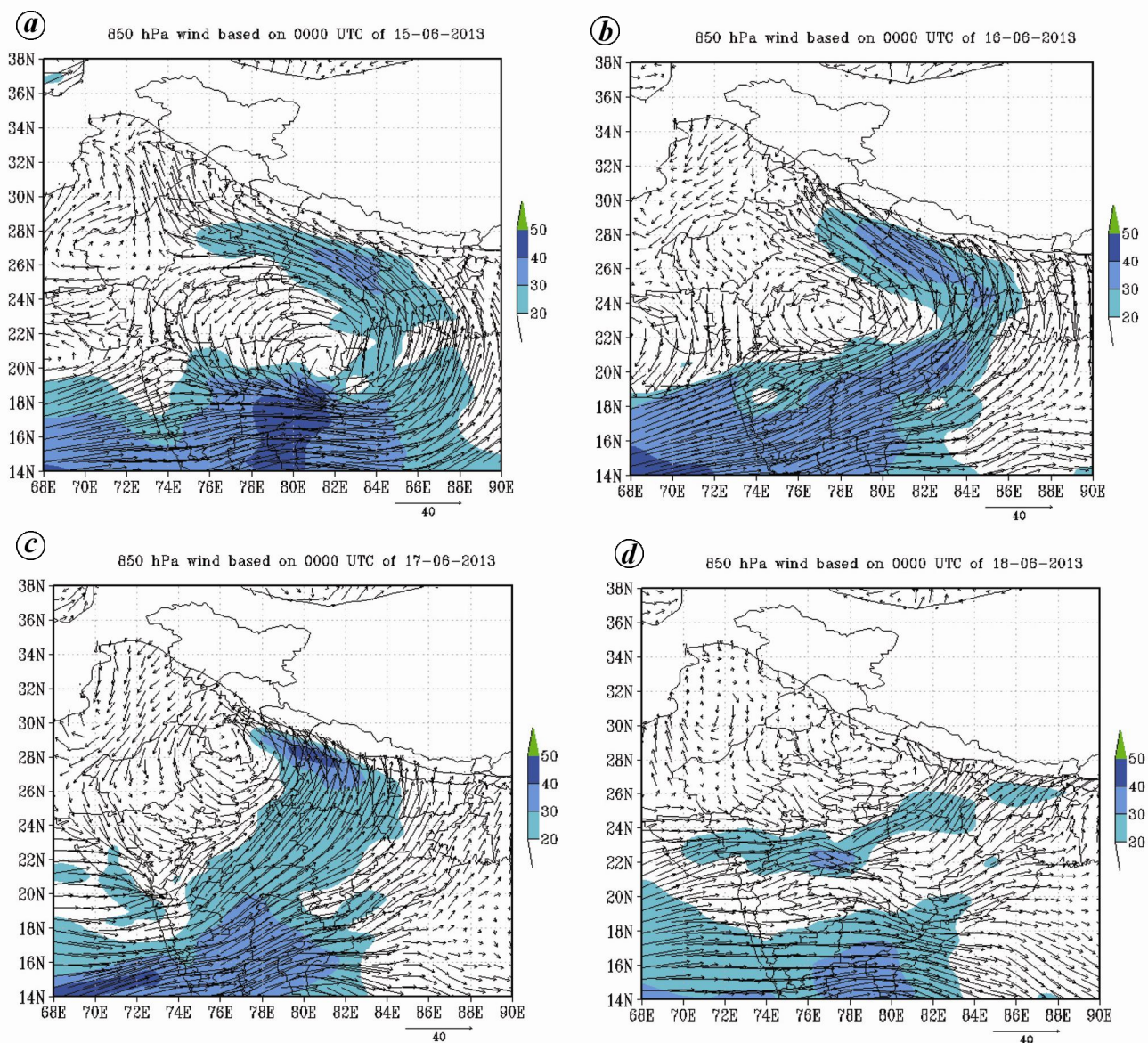




**Figure 4.** Flow pattern of 200 hPa at 0000 UTC.

North India from west to east during the period from 15 to 17 June 2013. Close interaction of the westerlies and the monsoon system during 15–17 June, with the north-south oriented orography of the Western Himalayas, created a convergence line which was virtually locked over Uttarakhand and its neighbouring regions for about three days. Simultaneously, the zonally oriented belt of lower atmospheric air, narrows and strengthens (~40 kt) through 15, 16 and 17 June and pumps a lot of moisture from BoB into the Himalayan ranges from the surface up to 500 hPa. The moisture flux rapidly rose over the region. Initially, when the monsoon low was located over southeast Madhya Pradesh (MP) and adjoining Chhattisgarh at 0000 UTC on 15 June, the southeasterly current was strongest (30–40 kt) over the northern plains of

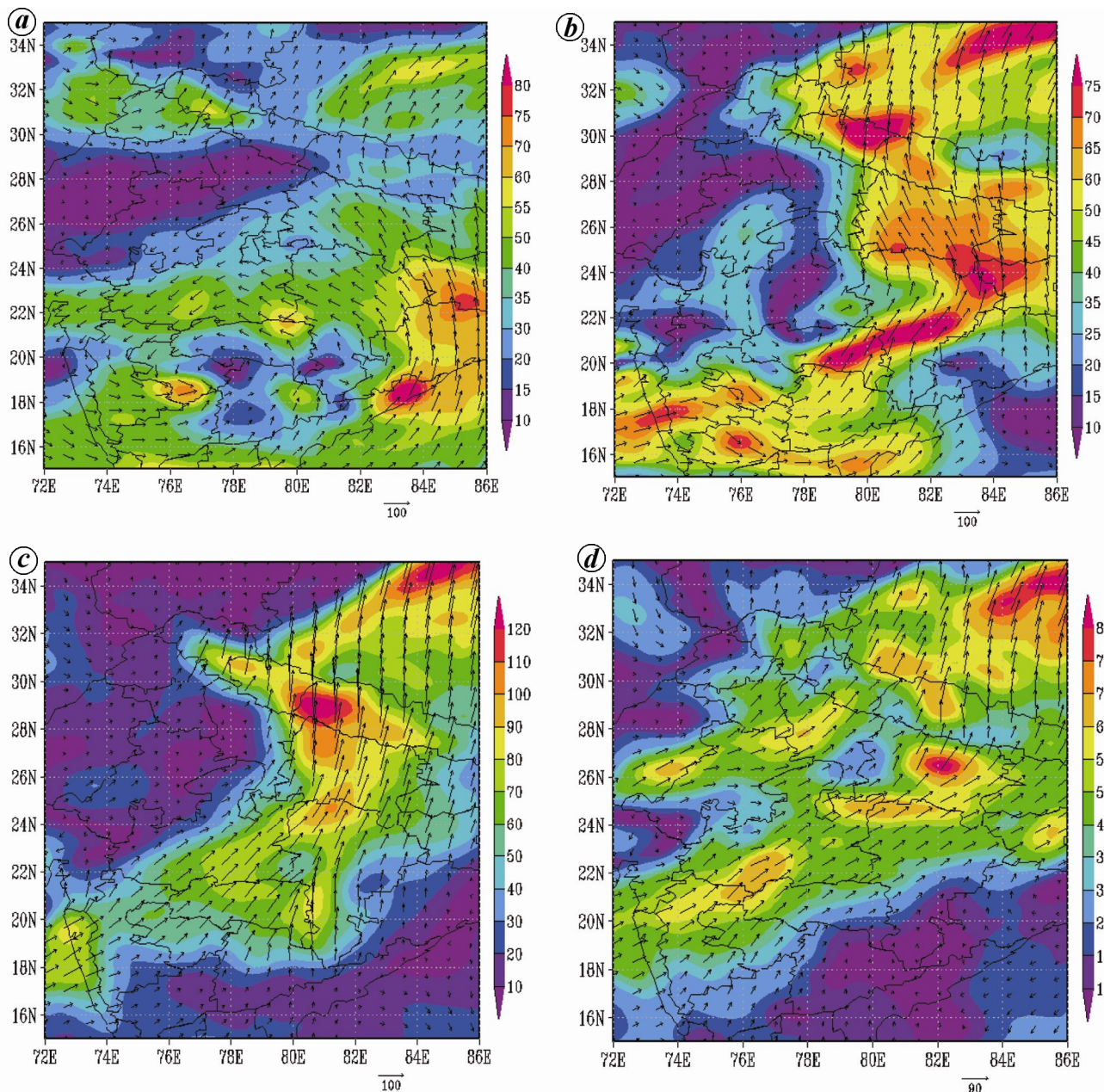
India at the northern periphery of the system. Moisture flux of the order of 60 (g/kg m/s) was observed in the model analysis field over the region, in association with the western disturbance (Figure 6a). At 0000 UTC on 16 June, the northwestwards movement of the low pressure system shifted the monsoon current maximum over west Uttar Pradesh (UP). Associated moisture flux values of the order of 75 (g/kg m/s) were noted over the region (Figure 6b). At 0000 UTC on 17 June, the low pressure system moved further northwestwards and was located over east Rajasthan. The associated monsoon current further strengthened ( $\geq 40$  kt) and shifted over west UP and Uttarakhand (Figure 5c). Associated increased moisture flux of the order of 120 (g/kg m/s) was noted over the region (Figure 6c). The moisture feed into North India on



**Figure 5.** Flow pattern of 850 hPa at 0000 UTC.

**Table 1.** Location of the low pressure area

Date and time	Location of the low pressure area
1200 UTC 12 June 2013	Northwest Bay of Bengal (BoB) and adjoining Odisha and north coastal Andhra Pradesh (AP)
0000 UTC 13 June 2013	Northwest BoB and adjoining Odisha and north coastal AP
1200 UTC 13 June 2013	South Odisha and its neighbourhood
0000 UTC 14 June 2013	Central parts of Odisha and its neighbourhood
1200 UTC 14 June 2013	Chhattisgarh and adjoining Odisha
0000 UTC 15 June 2013	Southeast Madhya Pradesh (MP) and adjoining Chhattisgarh and Vidarbha
1200 UTC 15 June 2013	West MP and its neighbourhood
0000 UTC 16 June 2013	West MP and its neighbourhood
1200 UTC 16 June 2013	East Rajasthan and its neighbourhood
0000 UTC 17 June 2013	East Rajasthan and its neighbourhood
1200 UTC 17 June 2013	Northeast Rajasthan and the adjoining area of Haryana
0000 UTC 18 June 2013	Became less marked and an upper air cyclonic circulation over north Rajasthan and its neighbourhood
1200 UTC 18 June 2013	Upper air cyclonic circulation over Haryana and the adjoining west Uttar Pradesh

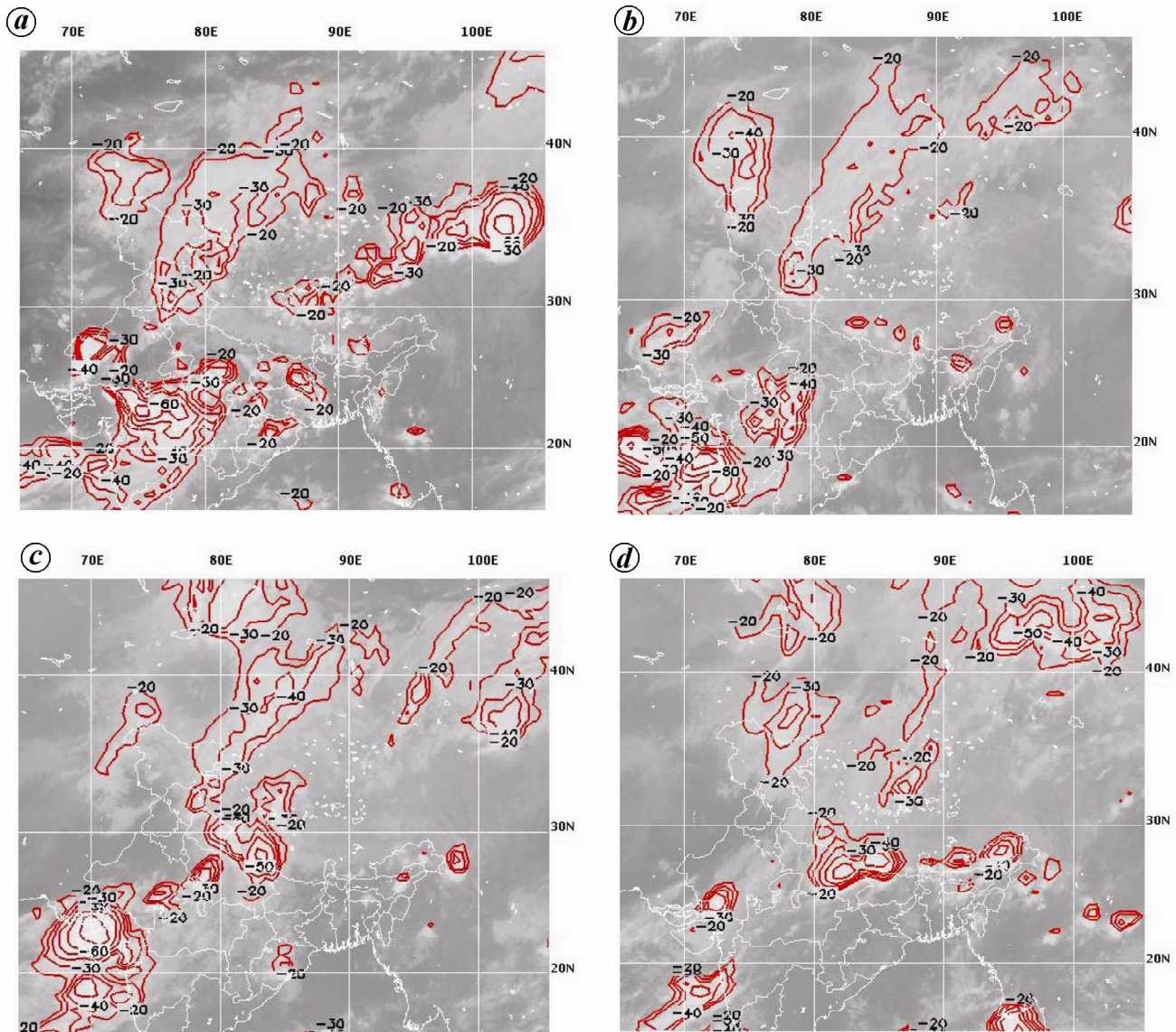


**Figure 6.** Wind vector (m/s) and moisture flux (g/kg m/s) analysis of 500 hPa at 0000 UTC: *a*, 15 June; *b*, 16 June; *c*, 17 June; *d*, 18 June 2013.

15 and 16 June was from the Arabian Sea as well as from BoB, while on 17 and 18 June, the monsoon current drew in moisture over the region primarily from the Arabian Sea (Figure 6 *c* and *d*). On 0000 UTC of 18 June, the low pressure system became less marked and persisted over north Rajasthan as a cyclonic circulation. The monsoon current significantly weakened to 5–10 kt over the Uttarakhand region and there was no southeasterly component of monsoon current from BoB (Figure 5 *d*).

Figure 7 *a–d* shows the KALPANA-I satellite imagery with cloud top temperature (CTT) indicating the presence of western disturbance and strong convection. The convective

cloud mass of CTT  $-30^{\circ}\text{C}$  was observed over Punjab, Uttarakhand, HP and Jammu & Kashmir on 15 June 2013. The convection zone moved northeastward and was concentrated over HP and Uttarakhand on 16 June. The convective zone further moved slightly eastward and concentrated over Uttarakhand and west UP on 17 June, and over west UP on 18 June 2013. The analysis shows that the convective zone persisted over Uttarakhand during 15–17 June. Strong cyclonic vorticity of order  $6 \times 10^{-5}$  at 500 hPa was noticed over central Uttarakhand on 16 June (Figure 8 *a*). On 17 June, positive vorticity was observed over most parts of Uttarakhand, with two



**Figure 7.** KALPANA-I satellite imagery with cloud top temperature: *a*, 1200 UTC 15 June; *b*, 0030 UTC 16 June; *c*, 0000 UTC 17 June; *d*, 0000 UTC 18 June 2013.

maximum cores of  $14 \times 10^{-5}$  over the western and eastern parts of the state (Figure 8 *b*). This indicates occurrence of interaction (convergence) between the westerlies and strong southeasterly monsoon current. As a result, there was development of strong vertical velocity (up to 3 Pa/s) at 500 hPa over most parts of Uttarakhand (Figure 9 *a*), with a core 3 Pa/s over southwest and southeast Uttarakhand on 16 June. On 17 June, there was strong vertical velocity (3–4 Pa/s) over southwest Uttarakhand (Figure 9 *b*). This interaction triggered the heavy to extremely heavy rainfall causing floods across the region.

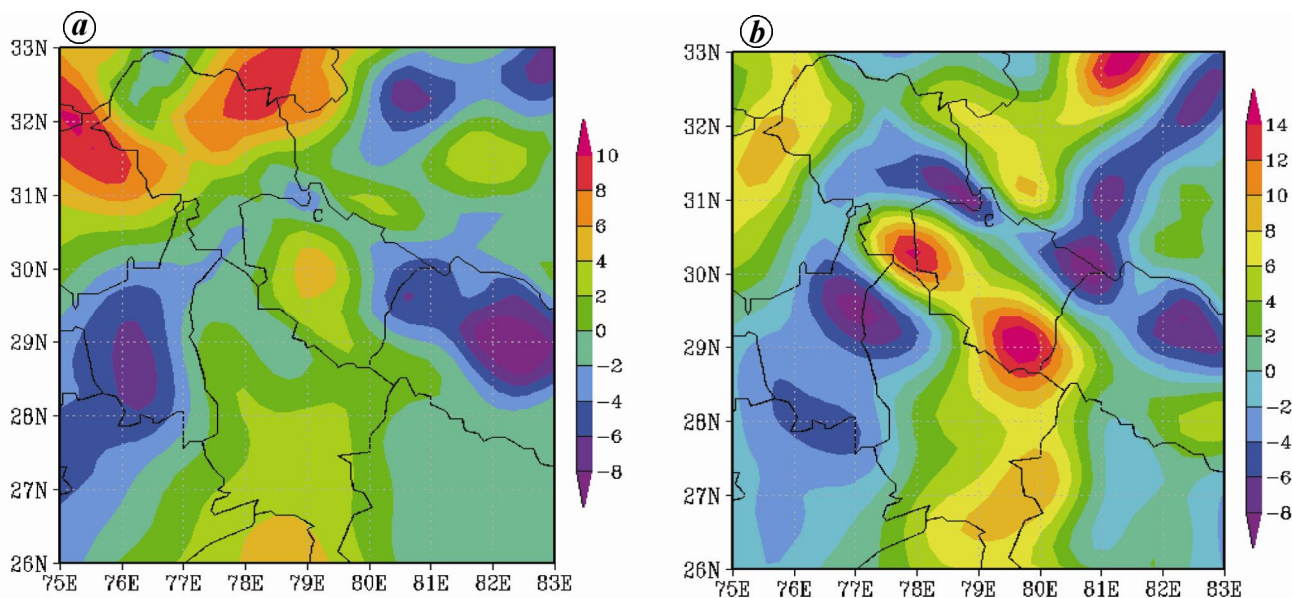
### Radar analysis of the rainfall episode

Two S-band single-polarized Doppler weather radars (Beijing METSTAR) of IMD at Patiala and Delhi have

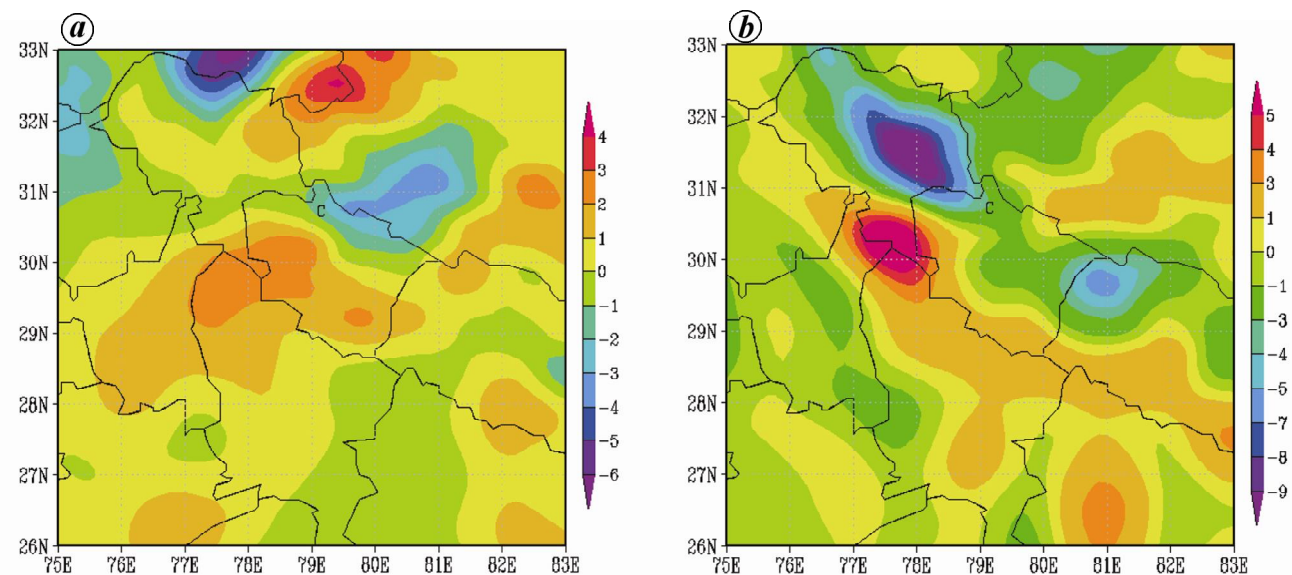
been used to study the weather episode. Figure 10 displays the two radars and the data range used for studying this weather episode over Uttarakhand. The epicentre of the devastating flash floods was Kedarnath ( $30.73^{\circ}\text{N}$ ,  $79.07^{\circ}\text{E}$ ), which is also marked in the figure. In order to obtain maximum information of the cloud systems, the data of the two radars are merged. A mosaic of the reflectivity data has been created using the w2merger tool of the Warning Decision Support System software (WDSS-II), whose usage is extensively described by Roy Bhowmik and co-workers<sup>7,8</sup>. Also, since Kedarnath falls outside the range of velocity data of both radars (250 km), the focus of this study is solely on the reflectivity data of the two radars.

The reflectivity data mosaic reveals that the initial clouding over the North Indian region associated with the movement of the westerly trough over the region was to





**Figure 8.** Relative vorticity ( $\times 10^{-5} \text{ s}^{-1}$ ) of 500 hPa at 0000 UTC: *a*, 16 June; *b*, 17 June 2013.



**Figure 9.** Vertical velocity (Pa/s) of 500 hPa at 0000 UTC: *a*, 16 June; *b*, 17 June 2013.

the west of Delhi, over Rajasthan and adjoining Pakistan at about  $32^{\circ}\text{N}$  on 14 June 2013, to the west of the radar at Delhi, moving in a east-southeasterly direction. On 14 June, before interacting with the monsoon system, the initial cells due to the westerly trough were taller (30–35 dBZ level is at 10 km height), of small spatial extent, more intense (maximum reflectivity of the order of 55 dBZ), and often organized into squall lines. Around the same time, the cloudiness due to the monsoon low moved northwestward, and at 1130 UTC on 15 June, interacted with the westerly trough and formed a clear northeast–southwest convergence line zone between the two cloud systems ( $31.62^{\circ}\text{N}$ ,  $79.87^{\circ}\text{E}$  and  $27.10^{\circ}\text{N}$ ,

$75.93^{\circ}\text{E}$ ; Figure 11 *a* at 1400 UTC when the systems are partially merged). As the system moved eastward and interacted with the moist flow associated with the monsoon low pressure system, the average height and intensity of the clouds decreased (20–25 dBZ level of reflectivity values at 8–10 km height). This line of discontinuity, though initially northeast–southwest oriented, gradually became north–south oriented along  $77.5^{\circ}\text{E}$  by the merging of the two cloud systems and blocking of further movement of the northern part of the line of discontinuity by the Himalayan orography (Figure 11 *b* is a snapshot at 1536 UTC when the line of discontinuity is oriented in a north–south direction). The line of discontinuity was

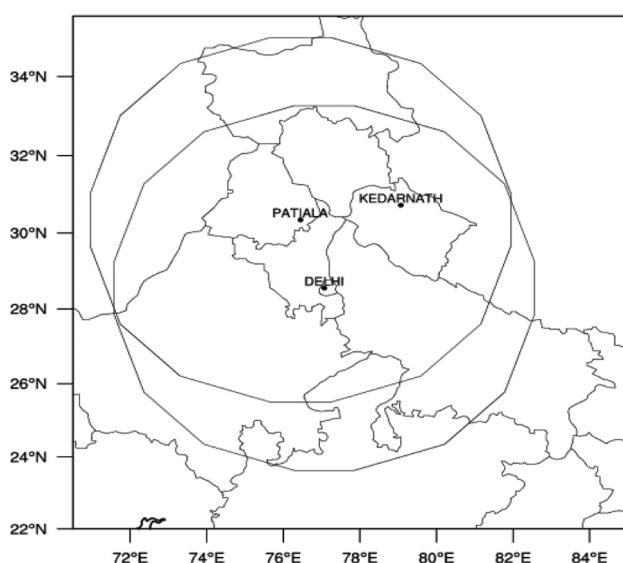
semi-stationary for the next two days. During this period, the region of high wind and moisture convergence became one where a mesoscale convective system (MCS) formed, with new convective cells regenerated in the same area. Initial convection and maximum rainfall according to the radar reflectivity data, were confined mainly to the districts of Dehradun in Uttarakhand, Sirmour in HP, Yamunanagar in Haryana and Saharanpur in UP on 15 and 16 May 2013. This flooded the upper catchment of the river Yamuna, causing flash floods there on 15 and 16 June. The convergence zone slowly moved northeastward thereafter, and brought rainfall over the Dehradun, Rudraprayag, Chamoli, Almora, Nainital and Uttarkashi districts on 16 and 17 June. This flooded the upper tributaries of the Ganga (Mandakini and Alakananda among others), causing flash floods downstream of the river up to Haridwar. The main rainfall period over Kedarnath was triggered by cloud systems moving eastward from west Uttarkashi, and northward over this region from the Chamoli and Rudraprayag districts after 10 UTC on 16 June, which continued into the morning hours of 17 June. The most intense clouds appear to have struck the Kedarnath region early in the morning of 17 June 2013, when a 40 km wide cell migrated northeastwards to over this region at 0000 UTC from over the Rudraprayag district. This lasted for an hour, directly over Kedarnath, before dissipating. As the convergence line weakened on 17 June, the cloud system became disorganized and dissipated on the afternoon of 17 June (Figure 11 *c* at 1146 UTC on 17 June).

The characteristics of the cells regenerating along the convergence line were studied by both radars. Although the radar at Patiala is closer to Kedarnath, the intervening hills cause severe beam blockage to the east. This causes

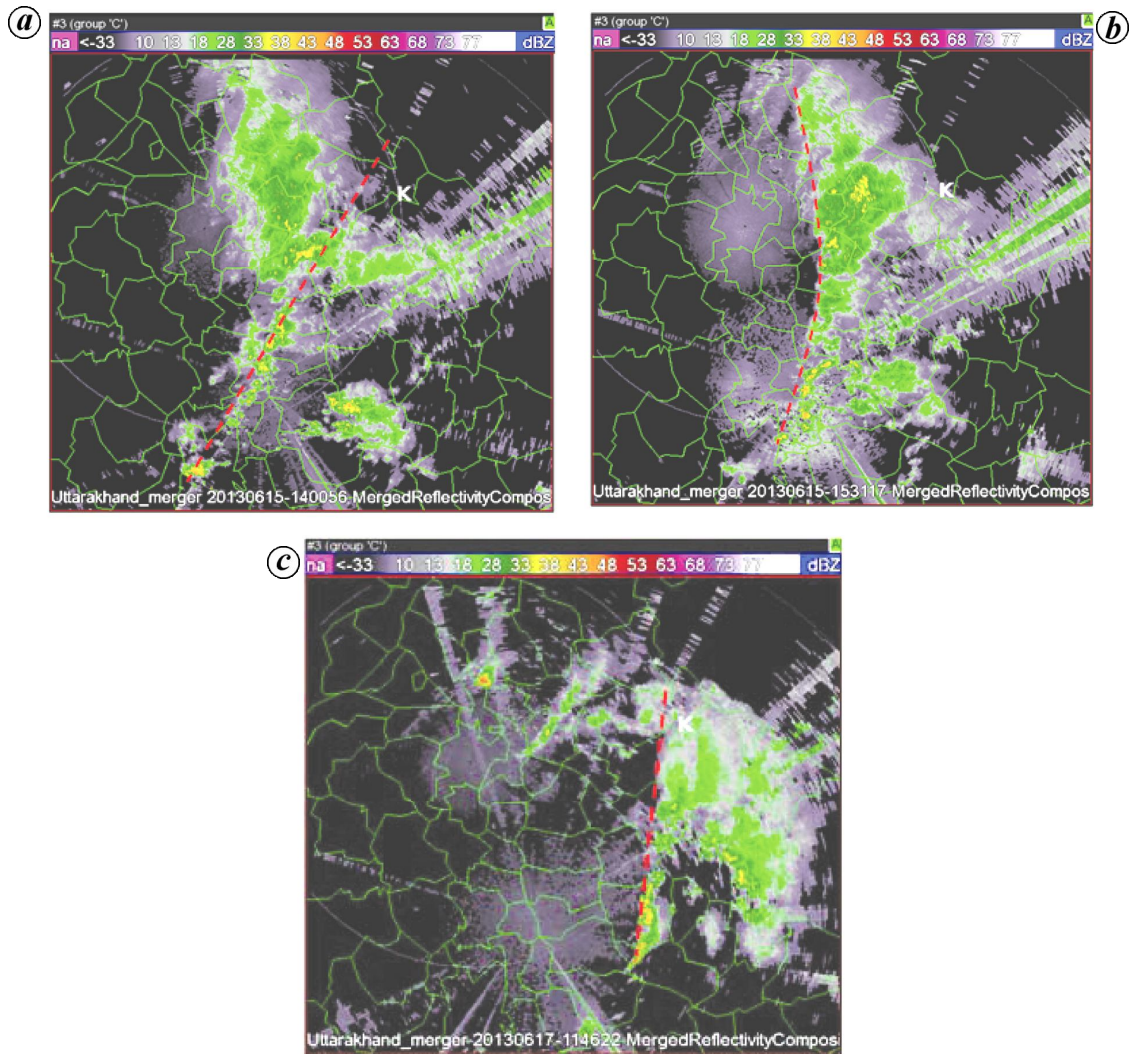
an error in the estimation of the height of the clouds by the radar in the east. They appear much shorter than actual when a vertical cut is drawn through the cells (Figure 12 *a*). On the other hand, the radar at Delhi, being far away from Kedarnath, does not suffer from much beam blockage and provides more information of the weather systems in the neighbourhood of Kedarnath, although at a coarser resolution and of the upper atmosphere (Figure 12 *b*). A vertical cut at the same position from both radars reveals that the mesoscale convective cloud system was composed of clouds with short height, broad width and long lifetimes. The 20 dBZ height of most of the clouds was below 10 km. The maximum intensity at the core of the cells also did not exceed 40 dBZ in most instances. However, these cells were often wide, of the order of 30–40 km and had long lifetimes (1–2 h). Previous observations from the TRMM precipitation radar have noted that deep convective cores (deep wide erect echoes with the 40 dBZ echo top reaching heights >10 km) and wide convective cores (40 dBZ echo >1000 sq. km in horizontal dimension) form along the Western Himalayan indentation during the monsoon season<sup>9,10</sup>. Our analysis shows that the clouds associated with the westerly trough, prior to its interaction with the monsoon low, were mostly of the former type. These were shorter-lived, taller and moved very fast. On the other hand, the clouds in the zone of convergence were mostly of the latter type. While not all clouds were wide, strong interaction between the two weather systems and the strong moist current into the region resulted in long-lived cells which resulted in a lot of rainfall in the location.

### Comparison with Leh 2010 flash flood episode

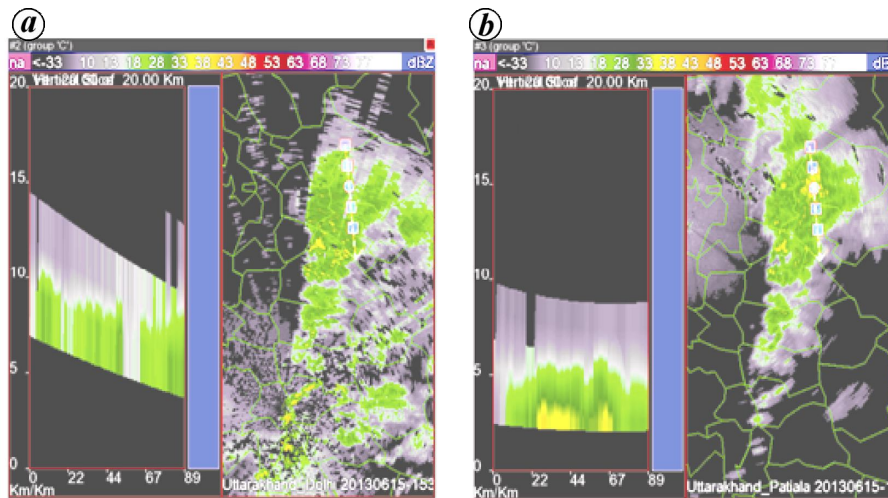
On account of the fact that the flash floods over Leh in 2010 and the current flash floods over Uttarakhand in 2013, both occurred over the Western Himalayas during the monsoon season, their commonality and distinctiveness is a matter that needs to be addressed. Studies<sup>11</sup> have noted that the Leh flood was the result of a series of mobile mesoscale westward-propagating MCSs forming upstream over the high terrain of the Tibetan Plateau and then moving over the steep Himalayan face where they became invigorated by the moist monsoon flow. In contrast, the Uttarakhand episode was non-propagating and fixed in location over a steep terrain, along a convergence line, where the cells were continuously regenerated over the same region. The cloud systems forming over the region for both cases were similar in that the cells were fat, long-lived clouds with large stratiform outflows. Such clouds, in both instances, did not cause a cloud-burst-type rain event. Rather, the clouds and the associated stratiform outflows provided long periods of low-intensity rain over steep terrain and narrow catchments. The pumping of moist BoB air in a sustained manner,



**Figure 10.** Reflectivity data range of the S-band Doppler radars at Delhi and Patiala.



**Figure 11.** *a*, Mosaic composite reflectivity data from DWR Patiala and Delhi displaying the line of discontinuity (red dotted line) at 1400 UTC of 15 June, formed at the convergence zone of the westerly trough and the monsoon low pressure system (**K** indicates the location of Kedarnath). *b*, Line of discontinuity (red dotted line) orients in a north-south direction as the southern portion of the line of discontinuity moves eastward faster than the northern end. *c*, Line of discontinuity (red dotted line) decays as the two weather systems cease to interact on 17 June 2013.



**Figure 12.** A vertical cut through the reflectivity data of (*a*) DWR Delhi and (*b*) DWR Patiala reveals that if the data of both radars are simultaneously analysed, it indicates that most of the cells are not very tall (20 dBZ at 10 km height), but interact closely. Snapshot at 1530 UTC of 15 June 2013.

through many hours into the region, referred to as an 'easterly jet' for the Leh episode<sup>11</sup>, resulted in long-lived, regenerative MCS-type systems in both cases. However, in the case of Uttarakhand, the wind speed was 40 kt and was over northern Bihar and UP, whereas in the Leh 2010 episode, it was further north, over the Tibetan Plateau and about 60 kt. This may be due to the different locations of the monsoon low in both cases. Some moisture was also drawn from the Arabian Sea in both cases.

## Conclusions

Widespread heavy rainfall occurred over Uttarakhand during 16–18 June 2013 and some stations in Uttarakhand reported extremely heavy rainfall (exceeding 24.5 cm) on 17 and 18 June. This extreme event resulted from the interaction of the mid-tropospheric westerlies and lower tropospheric strong southeasterly monsoon current over the region. The strong SW monsoon current developed due to the presence of a low pressure system, which formed over northwest BoB on 12 June 2013. The system moved in the northwest direction and reached up to northeast Rajasthan. The system was located over MP and northeast Rajasthan on 16–18 June and dissipated in the evening of 18 June. During the period, a western disturbance moved across North India from west to east. The westerlies and the monsoon system virtually locked over Uttarakhand and its neighbouring regions during the period and there was moisture feeding both from the Arabian Sea and BoB. The area of heavy rainfall coincided with the upper-level divergence associated with the westerly trough (east of the trough) and right exit of the westerly jet stream. Analysis of dynamical and thermodynamical features based on model analysis clearly indicated an appreciable rapid growth of moisture flux from 60 (g/kg m/s) of 15 June to 120 (g/kg m/s) on 17 June. The two systems (mid-tropospheric westerly system and monsoon system) together pumped in the huge amount of moisture into the region between surface and 500 hPa. The vorticity pattern at the convergence zone indicates the intense interaction between the westerlies and strong southeasterly monsoon current. A combination of the two factors, i.e. a deep and long-lasting convergence line with high vorticity values, coupled with huge amount of moisture feeding from the surrounding seas, provided the ideal thermodynamic and dynamic environment for the development of long-lived cells over this region. Radar analysis of clouds also shows that the line of discontinuity was quasi-stationary. The cells that formed over the region were not tall, but wide, with strong interaction between them, that resulted in long lifetimes of the cells. This triggered the heavy to extremely heavy rainfall event

causing severe floods, landslides and large-scale loss of lives over the region.

The similarities with the Leh 2010 flash flood episode indicate that the relative positions of the Tibetan high, monsoon low pressure system, westerly troughs and the position of the westerly jet stream appear significant factors in the pumping of huge amounts of moisture into the Western Himalayas. It will be interesting to study more such cases of rainfall events to provide better forecast support for predicting such anomalous events.

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