Indian Ocean tsunami have resulted in permanent loss of vital habitat and coastal features along the Katchall Island in Nicobar (Figure 6 *i*).

Spatial inventory of shoreline changes using satellite data of 1989–1991 and 2004–2006 time frame in GIS environment has been created for the entire Indian coast on 1 : 25,000 scale. The results show that 3829 km (45.5%) of the coast is under erosion, 3004 km (35.7%) is getting accreted, while 1581 km (18.8%) of the coast is more or less stable in nature. Highest percentage of the shoreline under erosion is in Nicobar Islands (88.7), while percentage of accreting coastline is highest for Tamil Nadu (62.3) and Goa has highest percentage of stable shoreline (52.4). The cause of severe erosion along Nicobar coast is probably due to the Indian Ocean tsunami of December 2004. In many other parts of the Indian coast, coastal erosion occurs due to the construction of dams in catchment areas of rivers and developmental activities such as construction of ports/fishing harbours/ jetties. The analysis shows that the Indian coast has lost a net area of about 73 sq. km during 1989–1991 and 2004–2006 time frame. In Tamil Nadu, a net area of about 25.45 sq. km has increased due to accretion, while along Nicobar Islands about 93.95 sq. km has been lost due to erosion. The inventory along with current status of coastal protection measures taken up by concerned state departments has been used to prepare a *Shoreline Change Atlas of the Indian Coast*. The baseline data are aimed towards initiating appropriate action for protecting the Indian coast by concerned Maritime states and UTs besides use by the scientific community as well decision-makers of the country.

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Heavy rainfall in the Kedarnath valley of Uttarakhand during the advancing monsoon phase in June 2013

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During the monsoon season of 2013, the advance of monsoon over northwest (NW) Indian region showed large abnormality as arrival of rainfall over Punjab, Himachal Pradesh (HP), Uttarakhand, Haryana and Delhi occurred between 13 and 16 June 2013, nearly twice the standard deviation earlier than normal. Such an early arrival by mid-June has been exceptional. The event was marked by unprecedented very heavy rainfall between 14 and 18 June 2013 over different meteorological sub-divisions of NW India. The event also led to human tragedy in Uttarakhand,

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in which many local people and pilgrims lost their lives. This heavy rainfall in fact moved from Punjab and HP during 14 and 15 June 2013 to Uttarakhand. The rainfall between 14 and 18 June 2013 over NW India was highly organized and it was continuously sustained with mesoscale enhanced intensity over Uttarakhand, which dispels the opinion about cloudburst. The present communication is aimed to study the observational aspects of the vigorous and rapid advance of monsoon rainfall over NW India and its intensification during 15–17 June 2013 over Uttarakhand.

Keywords: Heavy rainfall, landslides, monsoon season, rapid advance.

THE Indian summer monsoon (ISM) is a seasonally locked regional climate system with an annual cycle that occurs every year with great regularity and passes through different phases on the intraseasonal scale, such as the onset and advance of the monsoon (mid-May to mid-July), peak monsoon phase (July to August) and withdrawal of the monsoon (mid-September to mid-October). Rainfall during different phases shows large temporal and spatial variability and so is the case for the quantum of seasonal rainfall. Although every year in the monsoon season (June to September), the broad contours of the evolution of the monsoon remain the same, a canvas emerges as a natural process of evolution of the monsoon in a season showing marked variability through dynamically coupled ocean–atmosphere–land interactions. The season begins when rainfall commences over the mainland India at its southwestern corner state of Kerala, known as the 'Monsoon onset over Kerala' (MOK). Figure 1 shows the classical dates of onset and advance of monsoon rainfall over India based on the data of nearly 40 years of five-day average rainfall over different stations in India. According to India Meteorological Department (IMD), the climatological date of MOK is 1 June (standard deviation of 7–8 days), advance over Mumbai is 10 June, Kolkata is 7 June and Delhi is 30 June (Figure 1). The standard deviation over southern and peninsular India is 7–8 days, but over northwest (NW) India it becomes 8–10 days.

Every monsoon season leaves behind certain important facets for which it becomes known for further studies. The monsoon season for 2013 will be known for exceptional rapidity and vigour of the monsoon in its advance phase and the havoc it caused over the Kedarnath valley in Uttarakhand, India, due to heavy rainfall and landslides. The heavy rainfall during the advance phase in June 2013 was not sudden, but evolved as a result of interactions between the WNW moving monsoon low pressure area from Odisha to Rajasthan, and almost synchronous movement of two western disturbances and the associated trough in middle and upper tropospheric westerly flow regime from Pakistan and neighbouring regions across Uttarakhand. The two independent rain belts associated with these systems merged from 25°N, 77°E to 35°N, 77°E, as a result of the dynamical interactions between the tropical and mid-latitude disturbances during the exceptionally rapid advance phase of the monsoon in 2013. A major disaster occurred on 16 and 17 June 2013 in Uttarakhand, which caused great damage in the region. There were reports that the huge loss of human lives and property was caused by heavy rainfall due to cloudburst, which led to sudden flash floods in the Mandakini and Saraswati river systems in Kedarnath valley of the state. Heavy rainfall events in the western Himalaya often result in landslides across the hilly terrain[1,2]. Cloudbursts too occur over this area in the monsoon season[3]. The TRMM rainfall has been examined over the western Himalaya, a region prone to deep convection during monsoon, such events have been studied with TRMM rainfall data using WRF model[4,5]. Climatological data show that in about 110-year period, 1880–1990, there have been only 31 cases, mostly all in July–September, causing extremely heavy rainfall over this region[6].

We analysed the evidence with regard to heavy rainfall and found that the rainstorm lasted for two days; it moved from east to west and produced widespread continuous heavy rainfall. These features dispel the opinion about the occurrence of a cloudburst as the scale of heavy rainfall in space covered the whole state and it lasted for two days (unlike a cloudburst phenomenon which occurs over a small area and exists for about an hour). According to our analysis, the two-day rainstorm (16 and 17 June 2013) over the state was caused by the disturbed large-scale atmospheric conditions as a consequence of the interaction between the westward-moving monsoon low and the eastward-moving deep trough in the mid-latitude westerlies, causing extremely heavy rainfall.

Uttarakhand (area 51,120 sq. km) is situated in the western Himalaya in northern India. Its borders touch other states of India like Himachal Pradesh, Uttar Pradesh and Haryana as well as countries like Nepal and China. The state has 13 districts and altitude varies from near sea level (districts of Haridwar, Roorkee and Udham Singh Nagar) to higher altitudes varying between 3 and 5 km. Himalayan rivers like the Yamuna, Bhagirathi, Alakananda, and Kali and Ram Ganga with their several tributaries drain the state. The state also receives heavy rainfall during the monsoon season with the average rainfall during the monsoon season being 123 cm, varying spatially from 50 to 200 cm. Environmentally the hilly regions of the state enjoy great scenic beauty. The hill tracks are quite fragile, as land/mud slides occur frequently because of heavy rainfall. Due to development work like road-building activity and building of major and small dams for generation of hydroelectricity, environmental degradation has been reported over the years. Within the higher altitudes of the state are situated important pilgrimage centres of Hindu and Sikh religions, which attract a large number of devotees to visit the shrines every year during

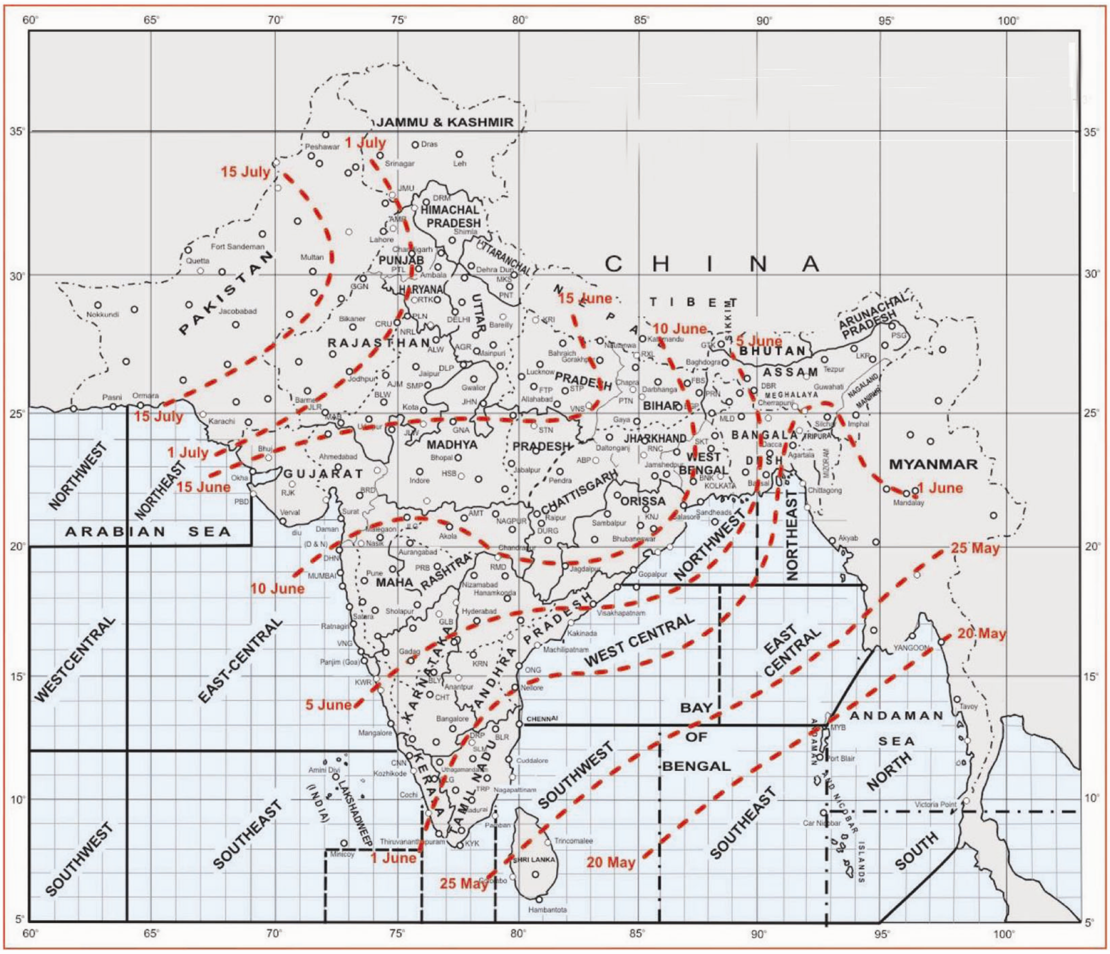

Figure 1. Normal dates of onset and advance of southwest monsoon over India (source: IMD[9]).

May and June. Due to this and also the development efforts, tourism industry has flourished during the last two decades, making both tourists and pilgrimage centres more prone to natural disasters.

For the monsoon season, IMD publishes in its weekly weather reports, daily rainfall for each day of the season as recorded at about 2600 rain gauge stations comprising IMD's manned surface network, Automatic Weather Station (AWS) and Automatic Raingauge (ARG) network of IMD, state raingauge networks, etc. The normal monthly rainfall over various districts has been calculated using average data for the period 1970–2000. Daily Indian precipitation analysis formed by merging rain-gauge data with the TRMM TMPA satellite-derived rainfall estimates from 14 to 19 June 2013 has been used to show rainfall over Uttarakhand region. The rainfall rates have been calculated for some of the stations with hourly rainfall recorded using automatic rain gauges installed in Uttarakhand.

The monsoon set in over Kerala on 1 June 2013, which is the normal date for its onset. The monsoon advanced rapidly along the west coast covering Karnataka, Konkan and Goa coasts by 8 June 2013. By 11 June 2013, the monsoon had covered the North East (NE) Indian states, peninsular India, Gujarat coast and even some parts of central India. The advance process became rapid between 13 and 16 June 2013, as the monsoon swept across the rest of the country in about four days, a process which normally takes 20–30 days.

This was an exceptionally rapid advance as the monsoon covered the whole country in about 16–17 days from Kerala to west Rajasthan. For the 2013 season, the onset and advance over the entire country just occurred in one step between 1 and 17 June without any temporary hiatus anywhere.

We now examine the chief features which have emerged regarding the development of major synoptic systems in week 3, i.e. 12–19 June 2013. During this week, the explosive growth of the regional monsoon system took place with the formation of three centres of heavy or vigorous monsoon rainfall.

(i) Along the forward sector of the monsoon low pressure area migrating from Odisha to Vidarbha between 13 and 15 June, and to Madhya Pradesh on 16 June.

(ii) Along the entire west coast with the central region being off Konkan and Goa, and Gujarat state regions between 14 and 17 June due to active offshore trough.

(iii) Along the entire northwest (NW) India, the rainfall was heaviest over Uttarakhand region. The heavy rainfall was due to the western disturbance, ahead of the upper layer westerly trough. The moisture being supplied by easterly/southeasterly winds from the Bay of Bengal, aided by divergence ahead of the trough and the orography of Himachal Pradesh and Uttarakhand resulted in extremely heavy rainfall in this region from 15 to 17 June 2013. Figure 2 shows the longitude time section at 200 hPa meridional wind anomaly along 35°–45°N in the region of mean portion of subtropical jet stream from 11 to 21 June 2013. It shows the passage of a westerly wave from 10°E on 12 June 2013 to 70°E on 17 June 2013. The approach of an equator-ward penetrating westerly trough and its interaction with the monsoon low pressure area on 16 June 2013 were responsible for the unusual vigour of the monsoon on 16 and 17 June 2013 over Uttarakhand. Figure 3 shows the longitude time section for 850 hPa geopotential height and anomaly averaged for 20°–26°N. High negative anomaly at 85°E on 14 June 2013 and migrating westward to 75°E on 17 June 2013, was associated with the monsoon low pressure system. The airflow in the entire troposphere was anomalous, which led to the production and sustenance of a huge deck of stratified clouds over an area of 50,000 sq. km that produced sustained rainfall for 2–3 days over Uttarakhand (Figure 4). The wind flow had changed from east–west-directed to SW–NE directed from Konkan coastal area toward Uttarakhand through the corridor of Madhya Maharashtra and West Madhya Pradesh. The change in the direction of water vapour flux, as a result of the change in wind vectors brought massive water vapour flux convergence over the East Rajasthan–Haryana–Uttarakhand regions on 16 and 17 June 2013 (Figure 5). This resulted in intense rainfall over the region as measured during 16–18 June 2013. The marked change in the east–west-oriented wind anomaly field and the subsequent moisture transport to SW–NE-directed anomaly field on 16 and 17 June 2013 can be clearly noticed.

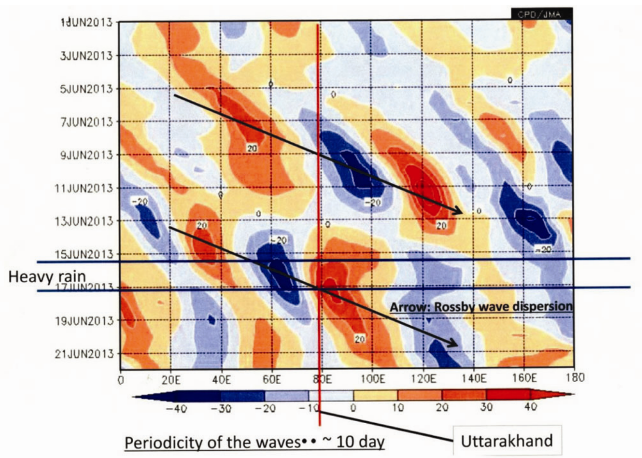

Figure 2. Longitudinal time section at 200 hPa meridional wind anomaly from 11 to 21 June 2013 (source: CPO/JMA).

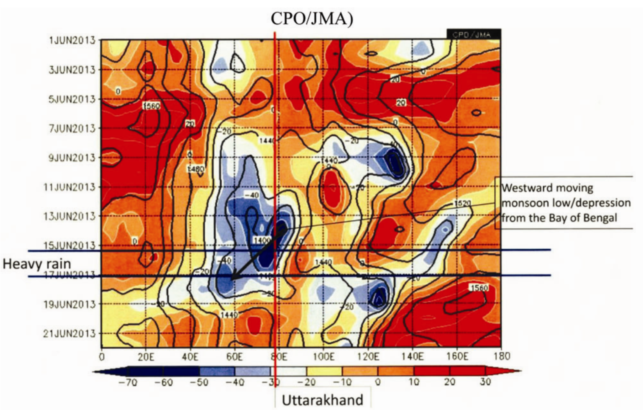

Figure 3. Longitudinal time section at 850 hPa geopotential height and anomaly from 11 to 21 June 2013 (source: CPO/JMA).

The highest one-day rainfall in the monsoon season over the western Himalaya generally varies from 15 to 60 cm and one-day probable maximum rainfall for the season varies from 50 to 70 cm. The frequency of heavy rainfall events is less in June, but increases in July and August. According to Dhar and Nandargi[6], 31 severe rainstorms have affected Uttarakhand and Uttar Pradesh region in 119 years over the period between 1880 and 1990. Of these, 25 have occurred in August and September, five in July and only one at the end of June. There has been no incidence of severe rainstorm in the middle of June because climatologically, the monsoon advance over Uttarakhand is towards the end of June. Severe rainstorm was defined by these authors to occur when the maximum point rainfall exceeded 20 cm for one day and cumulative rainfall for 2–3 days exceeded 25 and 30 cm respectively.

Table 1 presents statistics about the heavy rainfall events in June over Uttarakhand for the last 20 years (1991–2013). The table shows that in the past 20 years, 66 heavy rainfall events occurred between 1 and 15 June, out of which the highest events (20) occurred in 2000 and the next highest (9) in 2013. During the second fortnight of June (16–30), a total of 120 events of heavy rainfall have occurred in the past 20 years and the highest number of 60 events occurred in 2013 during the period 16–18 June. The predominant events of 2013 (11–18 June), 2008 (20–30 June) and 2000 (7–9 June) were associated with the advancing phase of the monsoon. However, the most striking feature has been the extensive area covered on 16–18 June 2013 (16 June, 16 stations; 17 June, 23 stations; 18 June, 16 stations). The heavy rainfall activity was widespread (>75% stations) over the state from 16 to 18 June 2013, which has never been seen in the past 20 years. Also during 16–18 June 2013, the rainfall exceeded

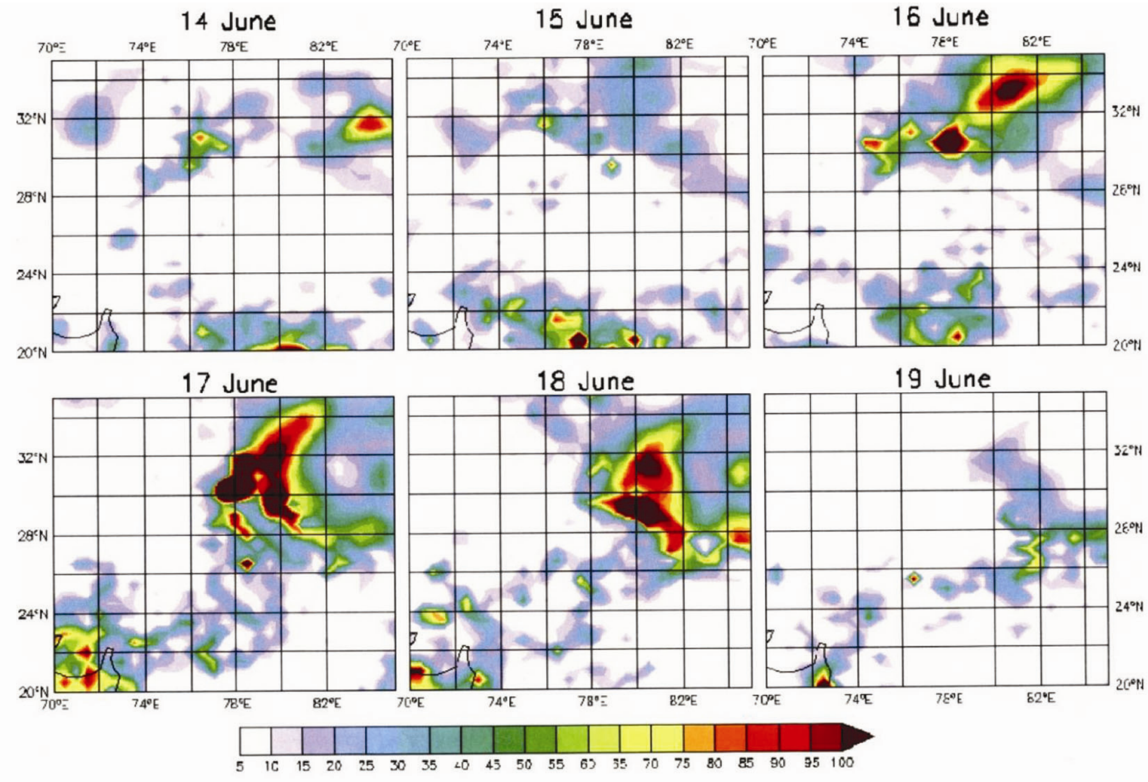

Figure 4. Daily Indian precipitation analysis formed by merging the IMD rain-gauge data with the TRMM TMPA satellite-derived rainfall estimates from 14 to 19 June 2013 (source: IMD and NCMRWF).

20 cm/day (exceeding the limit of one day severe storm set by Dhar and Nandargi[6]) at several stations, which was not the case in 2008 or even for other events listed in Table 1. Thus there is no doubt that the event covering 16–18 June 2013 was perhaps unique and unprecedented when very heavy rainfall occurred at the time of advance of monsoon over almost the entire state of Uttarakhand.

Table 2 shows district-wise mean daily rainfall for 13 districts of Uttarakhand. Each district has about 6–8 rain-gauge stations used for averaging daily rainfall. Wide-spread nature of rainfall began on 15 June 2013, but the average sub-division rainfall for the day was only 17.8 mm. Six out of 13 districts received heavy rainfall on 16 June 2013, with the state average being 71.7 mm (which falls in the heavy rainfall category). On 17 June 2013, there was considerable increase in the number of stations receiving heavy rainfall (10 out of 13 districts), but five districts received very heavy rainfall (≥ 125 mm). On 18 June 2013, seven districts received heavy rainfall, of which only one received very heavy rainfall. Thus the spatial coverage as well as the intensity of rainfall were highest between 03 UTC of 16 June and 0300 UTC of 17 June 2013, resulting in the average daily rainfall for the state being 13.3 cm, falling in the very heavy rainfall category. This again points to the exceptional nature of the rainfall as recorded for the state as a whole on 17 June 2013. Rainfall data for individual stations (Table 3), further support our inference drawn above, in which 15 out of 24 stations listed received 15 cm or more rainfall on 17 June 2013, the highest being 37 cm at Dehradun, the capital of Uttarakhand. The normal for the entire month of June for Uttarakhand is 157.3 mm. Some other districts too recorded 200–300% of mean monthly rainfall on these two days. The IMD observatory at Dehradun, registered 482 mm of accumulated rainfall for two days, i.e. 16 and 17 June 2013.

Tragic events occur when the rainfall intensity is high on short duration or three hourly average basis. This aspect has been examined with the hourly data recorded at nine automatic rain gauges for 16 and 17 June 2013 (Table 4). The maximum three hourly rain rates occurred in different three hourly intervals for both the days. For example, the three heaviest rain rates on 16 June 2013, were recorded between 0000 and 0300 UTC (68 mm), 1200 and 1500 UTC (55 mm), 0300 and 0600 UTC (56 mm) at Champwat, Danuri and Jolly Grand respectively. Similarly, on 17 June 2013, the heaviest three hourly rainfall occurred at Champawat (1200–1500 UTC), Nainital (0900–1200 UTC) and Pantnagar (0900–1200 UTC). Champawat was the worst affected receiving nearly 30 cm of rainfall in 1800 h between 2100 and 2400 UTC on 16 June and 1200 and 1500 UTC on 17 June 2013. The average maximum intensity per hour for Chapawat was about 17 mm/h, which is certainly not

Table 1. Heavy rainfall reported over Uttarakhand during 2002–2013

Year	Heavy rainfall in the month of June (cm)
1991	June 5: Banbasa–11; June 9: Chakrata–7; June 10: Narendranagar–8; June 11: Mukhim–16; Nanital–11; June 13: Kaladhungi–8; June 18: Dehradun–10; June 30: Banbasa–7
1992	June: Nil
1993	June 17: Mukteshwar–7; June 23: Mukhim–9; June 24: Banbasa–13; June 26: Haridwar–13
1994	June 24: Dehradun–10
1995	June 27: Banbasa–13; Dharchula–7
1996	June 13: Berinag–10; Rudraprayag–7; June 22: Dehradun–9; Banbasa–8; Nanital–7; June 25: Haridwar–22; Purola–8; June: 27 Berinag–7; June 28: Berinag–15; Banbasa–8; Munsiyari–7; June 29: Mukhim and Dakpathar–7 each
1997	June 4: Berinag and Pithoragarh–8 each; June 19: Champawat–9; June 28: Dehradun–9
1998	June 10: Dakpathar–7; June 11: Purola and Barkot–10 each; Haripur and Chakrata–7 each; June 12: Tiuni–10; Purola–9; June 17: Ranikhet–10; Mukteshwar–8; June 27: Chamoli–20; Banbasa–12; June 30: Nanital–9
1999	June 10: Dakpathar–7; June 12: Nanital–9; Munsiyari–8; June 17: Dehradun–12; Munsiyari–7; June 19: Nanital–17; Munsiyari–8; June 20: Munsiyari–9; June 22: Munsiyari–7
2000	June 7: Nanital–16; Munsiyari–9; June 8: Nanital–32; Munsiyari–16; Mukteshwar–15; Dharchula–12; Banbasa and Berinag–9 each; P. Nagar and Tiuni–7 each; June 9: Nanital–17; Mukteshwar–11; Mukhim–10; Haridwar; Dharchula and Keertinagar–9 each; Chakrata–8; P. Nagar and Tiuni–7 each; June 15: Munsiyari–8; June 16: Haridwar; Garhwal; Pauri; Berinag–10: each; Nanital–9; June 20: Mukhim–11; Munsiyari and Dhamkot–7 each; June 21: Uttarkashi–12; Ranikhet–9; June 26: Nanital–10; June 29: Haridwar and Luxur–9 each; Munsiyari–7; June 30: Mukhim–9; Dhamkot–7
2001	June 2: Dehradun–15; June 4: Dharchula–8; Munsiyari–7; June 12: Rudraprayag and Munsiyari–7 each; June 15: Haridwar–9; June 18: Banbasa–10; Dharchula–7; June 27: Munsiyari–16; Tiuni–12; June 29: Haridwar–11; Dehradun–7
2002	June: Nil
2003	June 2: Tehri–7; Pantnagar–7; June 25: Haripur–7; June 27: Banbasa–7
2004	June 14: Dehradun–10; June 17: Dehradun–8; June 18: Dehradun–12; June 20: Uttarkashi–12, Banbasa–7
2005	June 26: Hardwar–8; June 29: Didihat–9; June 30: Didihat–7
2006	June 30: Srinagar–11
2007	June 12: Kotdwar–10; June 14: Didihat–7; June 15: Kosani–10; June 25: Nainital–18; June 26: Uttarkashi–17; June 28: Pantnagar–9
2008	June 4: Nainital–7; June 10: Pantnagar–9; June 13: Dehradun–12; Roorkee–7; June 15: Dehradun–7; June 16: Kalagarh–9; June 17: Bambasa–8; Uttarkashi–7; June 19: Didihat–10; June 20: Haridwar–13; Marora–7; June 21: Rishikesh–7; June 22: Dehradun–9; June 25: Haridwar–7; June 27: Bosan–13; Marora–10; Rishikesh–9; June 28: Kalagarh–10; June 30: Rishikesh–9; Srinagar–8; Bosan–7; Haridwar–7
2009	28 June: Uttarkashi–12; 29 June: Banbasa–17; Khatima–11; Marora–8
2010	June 21: Dunda–9; Uttarkashi–7
2011	June 17: Pithoragarh–7; June 26: Rudraprayag–7; June 27: Banbasa–7; June 28: Uttarkashi–7; June 29: Champawat–11; Uttarkashi–9; Nainital–7; Landsdown–7; June 30: Chamoli–8; Uttarkashi–8; Mussoorie–7; Nainital–7
2012	June 25: Rudraprayag–7
2013	June 11: Banbasa–8; Landsdown–8; Haldwani–7; Mussoorie–7; June 12: Chamoli–7; June 14: Dehradun–9; June 15: Dunda–8; Jakholi–7; Kashipur–7
	June 16: Dehradun–22; Purola–17; Deoprayag–13; Uttarkashi–13; Tehri (CWC)–12; Tehri–12; Uttarkashi (CWC)–12; Dunda–12; Barkot–11; Haridwar–11; Jakholi–11; Haldwani–9; Rudraprayag–9; Karnaprayag–9; Mukteshwar–8; Kotdwara–7
	June 17: Dehradun–37; Mukteshwar–24; Hardwar–22; Uttarkashi (CWC)–21; Kosani–21; Haldwani–20; Nainital–18; Tharali–17; Tehri–17; Tehri (CWC)–17; Deoprayag–16; Bageshwar–16; Mussoorie–15; Roorkee–15; Joshimath–11; Jakholi–11; Champawat–10; Keertinagar–10; Rudraprayag–9; Karnaprayag–9; Almora–9; Pithoragarh–9; Chamoli–8
	June 18: Haldwani–28; Champawat–22; Mukteshwar–18; Nainital–17; Ranikhet–12; Pithoragarh–12; Pantnagar–11; Almora–10; Chamoli–10; Kosani–8; Karnaprayag–8; Tharali–8; Joshimath–8; Deoprayag–7; Keertinagar–7; Jakholi–7

exceptional as even 10 cm/h rainfall occurs at some places under vigorous monsoon conditions and in cloud-bursts. Deshpande *et al.*[7] have reported extreme rainfall for Dehradun as 101, 245, 279 and 289 mm for 1, 3, 6 and 12 h duration respectively, based on 1969–2005 records. The rainfall recorded during 16 and 17 June 2013 was much less than the maximum reported in the study[7].

As analysed by us, the event was not abnormal in rainfall intensity except that it had a large scale, covering the whole state with very heavy rainfall on 17 June 2013. However, the tragedy caused in Kedarnath valley has been unprecedented. Thus, besides heavy rainfall other factors must have contributed to the tragedy. Environmentalists ascribe it to the degradation in the environment caused by development activity and the rush due to religious tourism.

Dabhol *et al.*[8] have analysed the facts and plausible causes for the Kedarnath disaster. They have taken into account the glacier system (like the Chaurahari and Companion glaciers), the glacier lake or Mahatma Gandhi Sagar (a small glacier lake close to Mandakini River upstream of Kedarnath temple), and the confluence of the glacier-fed Saraswati River and the Mandakini River close to Kedarnath temple. It was the period of maximum glacier/snowmelt in the season. The rainfall which began from 12 June 2013 onwards over the glaciers, intensified

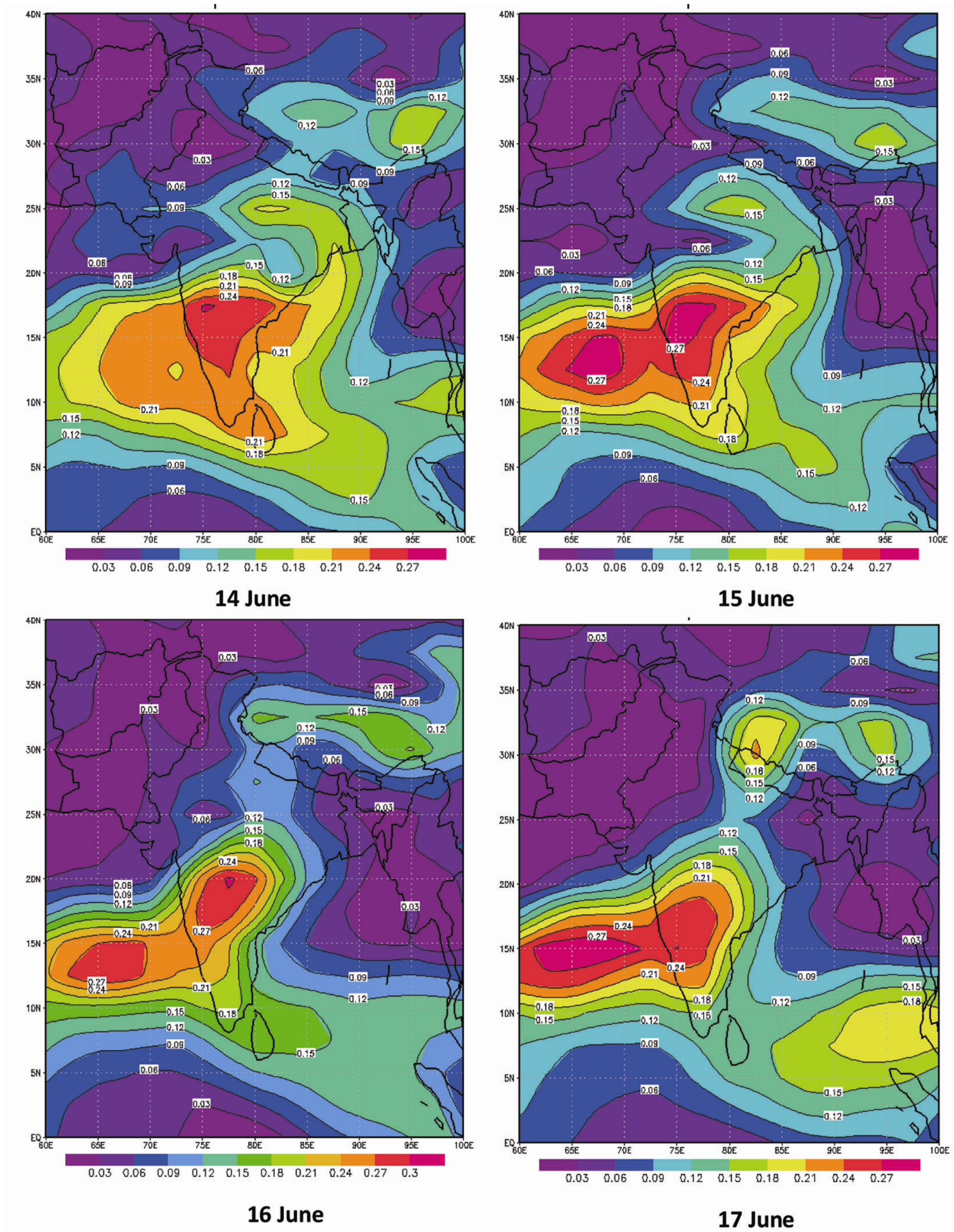

Figure 5. Moisture flux (gm*m/sec) at 850 hPa from 14 to 17 June 2013 (source: NCEP/NCAR Reanalysis).

between 15 and 16 June 2013. The heavy run-off from the heavy rainfall in the valley was at its peak between 12 UTC of 16 June and 3 UTC of 17 June 2013. There might have been some glacier lake outflow, though the lake is quite small to contribute huge amounts of water to rainfall and glacier melt run-off. Chaurabari glacier observatory recorded 325 mm of rainfall in 24 h between 1200 UTC of 15 June and 1200 UTC of 16 June 2013. The torrential rains and the resulting glacier melt flooded the Mandakini–Saraswati river system. The river water was charged with erosion and landslide debris. As a consequence, Dobhal *et al.*[8] concluded that the huge run-off (studded with debris) of surrounding fragile orographic features and glacial moraines moved toward Kedarnath town, causing havoc to human life and property. The Mandakini River, through development effort, has been channelized to flow into a new route away from Kedarnath town. However, due to heavy flow, the river began

Table 2. Mean rainfall recorded in various districts of Uttarakhand

District	Mean rainfall (mm)				Cumulative rainfall from 16 to 18 June 2013 (mm)	June normal rainfall (mm)
	15 June 2013	16 June 2013	17 June 2013	18 June 2013		
Almora	0.5	24.2	63.7	110	197.9	138.3
Bageshwar	3	48	183	73.1	304.1	–
Chamoli	22.6	61.5	113.1	85.2	259.8	102.9
Champawat	0.5	18.5	97	222	337.5	216.4
Dehradun	48.8	219.9	262.6	9.9	492.4	157.3
Garhwal Pauri	4.5	58.5	37	45.1	140.6	144.1
Garhwal Tehri	10.2	125.1	149.2	51.4	325.7	128.4
Haridwar	12.5	76.8	182.5	14.5	273.8	85.5
Nainital	10.7	71	204.1	210.5	485.6	219.2
Pithoragarh	0	11.2	85.5	117.2	213.9	254.7
Rudraprayag	41.4	97.2	100.1	62.1	259.4	212.2
Udham Singh Nagar	32.5	3.8	46.6	74	124.4	155.6
Uttarkashi	38.8	113.6	207.4	21.2	342.2	150.9
Subdivision rainfall	17.8	71.7	133.3	81	286.6	167.8

Table 3. Rainfall recorded in various rain-gauge stations/IMD observatories in Uttarakhand

Rain-gauge stations/ observatories	Rainfall (mm)			
	15 June 2013	16 June 2013	17 June 2013	18 June 2013
Jakholi	7	11	11	7
Dehradun	5	22	37	1
Uttarkashi	5	12	21	2
Mussoorie	4	<1	15	1
Chamoli	4	6	8	10
Tehri	3	12	17	5
Joshimath	3	4	11	8
Haridwar	2	11	22	1
Nainital	2	4	18	17
Tharali	1	6	17	8
Haldwani	1	9	20	28
Rudraprayag	1	9	9	6
Kotsdwara	1	7	2	<1
Deoprayag	<1	13	16	7
Karanprayag	<1	9	9	8
Mukteshwar	<1	8	24	18
Bageshwar	<1	5	16	6
Roorkee	<1	5	15	1
Pauri	<1	4	5	4
Champawat	<1	3	10	22
Almora	<1	3	9	10
Ranikhet	<1	2	4	12
Pithoragarh	<1	1	9	12

to take its old route close to the town. The extension of the township towards the old channel, under tourism activity, bore the brunt of the flood water and resulted in the tragedy.

The monsoon season of 2013 will be known for the exceptional rapidity and vigour of the monsoon in its advance phase and the havoc it caused over the Kedarnath valley in Uttarakhand due to heavy rainfall and landslides. For the 2013 season, the onset and advance over the entire country just occurred in one step between 1 and 17 June without any temporary hiatus anywhere.

The heavy rainfall during the advance phase over NW India was not sudden, but evolved as a result of interactions between the WNW-moving monsoon low from Odisha to Rajasthan and almost synchronous movement of two western disturbances and the associated trough in middle and upper tropospheric westerly flow regime from Pakistan and neighbouring regions across Uttarakhand.

Table 4. Three hourly cumulative rainfall in Automatic Raingauge (ARG) of India Meteorological Department (IMD) stations in Uttarakhand on 16 and 17 June 2013

IMD/ARG station	Rainfall (mm)							
	0830–1130 h	1130–1430 h	1430–1730 h	1730–2030 h	2030–2330 h	2330–0230 h	0230–0530 h	0530–0830 h
16 June 2013								
Bharsar		6	8	28	10		18	23
Champawat		13	9	13	14	23	33	68
Dhanauri (Haridwar)	10	13	23	55	10			22
Jolly Grant (Dehradun)	56	27	45	36	33	9	16	2
Matela		2	9	4	6	14	15	33
Nainital	1	10	27	16	39	49	33	42
Pantnagar Agro	0	1	4	0	6	15	19	13
Roorkee	15	14	30	47	7	4	7	24
Pithoragarh	2	9	4	5	3	11	13	22
17 June 2013								
Bharsar	17	29	32	0	0	0	2	0
Champawat	60	22	53	62	13	0	12	10
Dhanauri	6	5	0	0	0	0	0	0
Jolly Grant	1	2	0	0	0	0	0	0
Matela	39	13	18	11	2	7	10	0
Nainital	34	44	50	14	11	27	8	0
Pantnagar Agro	11	31	50	4	3	10	6	0
Roorkee	9	5	1	0	0	0	0	0
Pithoragarh	28	14	23	33	13	3	4	5

The present study could analyse and confirm the following:

(1) The exceptionally early advance of the monsoon from Odisha to entire India in just about 3–4 days between 13 and 17 June 2013 and the onset and advance of the monsoon in about 16 days against the average period of 45 days.

(2) Longitude time section for 200 hPa meridional wind anomaly along 35°–45°N and longitude time section for 850 hPa geopotential height and anomaly averaged for 20°–26°N emphasized the passage of a westerly wave and the interaction between the eastward-moving trough in mid-upper troposphere and westward-moving monsoon low in the lower troposphere.

(3) Analysis of wind anomalies showed large changes in the moisture flux from Konkan and Gujarat towards Uttarakhand through the corridors of the northern parts of West Madhya Pradesh between 16 and 17 June 2013.

(4) District-wise analysis of rainfall from a large number of ordinary rain gauges and automatic rain gauges over Uttarakhand for the period 13–18 June 2013 dispels the opinion about cloudburst, as the scale of heavy rainfall in space covered the whole state and it lasted for two days (unlike a cloudburst phenomenon which occurs over a small area and exists for about an hour).

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