

Dynamical features of incessant heavy rainfall event of June 2013 over Uttarakhand, India

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Abstract The southward penetration of mid-latitude westerlies and their interaction with monsoon current are harbinger of intense rainfall activity over northern and central India. Such synoptic condition prevailed during June 14–17, 2013, and unleashed relentless rainfall over the state of Uttarakhand. Observational aspects of this event have been explored using surface, satellite and reanalysis data. Precipitation features have been explored using data from Precipitation Radar Onboard TRMM satellite in conjunction with TRMM-TB42, Automatic Weather Station and Automatic Rain Gauge Station data. The ERA interim dataset has been used to explore prevalent synoptic conditions, and Modern-Era Retrospective Analysis for Research and Applications reanalysis fields revealed that prevalent synoptic features led to moisture flux convergence in lower troposphere. Vertically integrated water vapor transport over the India and adjoining oceanic region is evaluated to gain an insight into the dynamical mechanism of rainfall activity over Uttarakhand. Results reveal that interplay between movement of monsoon low along the monsoon trough resulting in strong low-level convergence and constant feeding of moisture from Arabian Sea and Bay of Bengal and strong upper-level divergence owing to southward intrusion of mid-latitude westerly trough resulted in heavy rainfall activity over Uttarakhand.

Keywords Heavy rainfall · Monsoon · AWS dataset · Water vapor transport · Dynamics

1 Introduction

The Indian state of Uttarakhand received heavy rainfall during June 15–17, 2013. This heavy rainfall in Uttarakhand during Southwest monsoon of 2013 caused a huge loss of life and an unprecedented amount of natural disaster (Srinivasan 2013; Kumar 2013).

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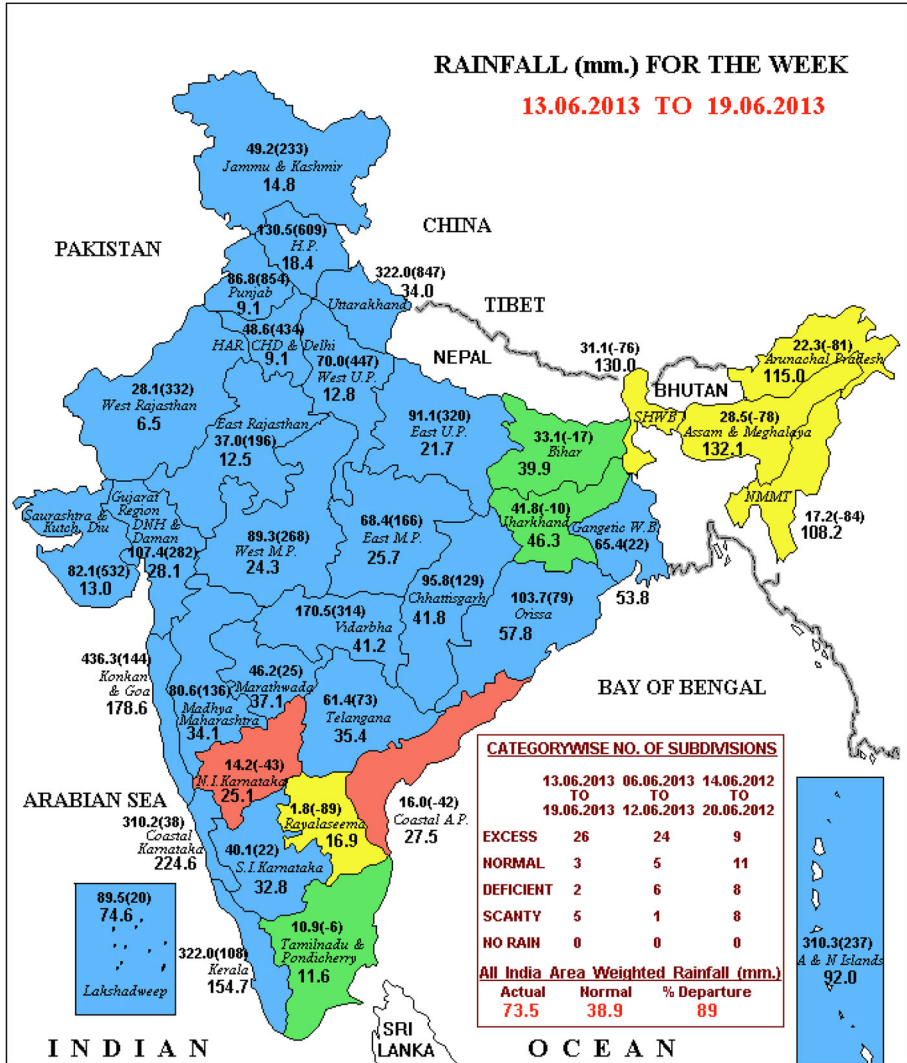
Before delving into this catastrophic incessant rainfall, it is important to understand the uniqueness of Southwest monsoon of 2013. In the year 2013, Southwest monsoon over India exhibited most rapid advancement in recent meteorological history. Since its onset over Kerala is on June 1, 2013, the monsoon engulfed entire Indian landmass by June 15, 2013. Convectively active phase of the Madden–Julian Oscillation and the associated systematic northward propagation of the east–west shear zone at the mid-tropospheric levels during the subsequent period helped faster advance of monsoon and increased rainfall activity over the country (IMD 2013). This was also aided by the formation and west-northwestward movement of a low pressure area along the east–west trough during the same period. On 16 June, the presence of this low pressure area over east Rajasthan and neighborhood superposed with a trough in the mid- and upper tropospheric westerlies provided conditions conducive for the large-scale convection and widespread monsoon rains over northwest India. The season witnessed the development of only two monsoon depressions and 16 monsoon lows (IMD 2013). The second monsoon low formed over the Bay of Bengal moved west-northwestwards during June 12–17, 2013, up to Rajasthan and Haryana, and its interaction with trough in the mid- and upper tropospheric westerlies during advance phase of monsoon caused relentless rainfall over Uttarakhand during June 14–17, 2013, and resulted in severe floods during June 16–17, 2013, in Kedarnath valley.

India Meteorological Department (IMD) reported departure of 847 % from normal in the rainfall volume over Uttarakhand region for the week of June 13–19, 2013 (see Fig. 1). However, such a large deviation from normal is not an exception for monsoon rainfall over these regions. Monsoon lows and depressions cause significant rainfall along and near the track of monsoon trough. Large part of Indian summer monsoon rainfall is an outcome of various synoptic-scale disturbances, many of which are intense (e.g., Rajeevan et al. 2008; Krishnamurthy and Ajayamohan 2010; Chaudhari et al. 2015). Events of heavy daily rainfall often exceeding 10 cm are common along the monsoon trough. Increasing trend in both frequency and intensity of extreme rainfall events over India during monsoon season in response to warming trend is reported by Goswami et al. (2006).

Stephenson et al. (1999) have pointed out that monthly and seasonal rainfall amounts may give a misleading impression that monsoon is a robust and slowly evolving system. The mean rainfall, however, is the rainfall averaged over many sporadic weather events having spatial scales from 100 to 1000 km. Previous studies (Houze et al. 2007; Medina et al. 2010; Romatschke and Houze 2011) have addressed the role of the Himalayas in modulating large-scale variability in Asian summer monsoon through convection and release of latent heat. In case of Uttarakhand heavy rainfall event, Himalayan barrier is also important. Dobhal et al. (2013) have reported that incessant rainfall during June 14–17, 2013, caused floods in Kedarnath Valley and situation become aggravated with melting snow and bursting of Chorabari lake (3960 m above mean sea level) located 2 km upstream of Kedarnath town. This led to the massive loss of infrastructure, human life and livestock at Kedarnath town and along banks of the river Mandakini. Joseph et al. (2014) have hypothesized that the negative phase of Arctic Oscillation might have caused the polar cold dry air to meddle with the tropical atmosphere. Srinivasan (2013) suggested that June 2013 Uttarakhand rainstorm event was an outcome of interaction between mid-latitude westerlies and monsoon current.

Therefore, it would be appropriate to investigate the event in terms of synoptic and meso-scale features to unravel its evolution and precipitation characteristics. In this study, dynamical perspective of the event is also explored. We have illustrated detailed

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LEGEND: ■ EXCESS (+20% OR MORE) ■ NORMAL (+19% TO -19%) ■ DEFICIENT (-20% TO -59%)
■ SCANTY (-60% TO -99%) ■ NO RAIN (-100%) NO DATA

NOTES:

- [a] Rainfall figures are based on operational data.
- [b] Small figures indicate actual rainfall (mm.), while bold figures indicate Normal rainfall (mm.)
 Percentage Departures of Rainfall are shown in Brackets.

Fig. 1 Weekly percentage departure in rainfall recorded in states of India for the week of June 13–19, 2013 (Source IMD)

analysis of synoptic conditions which lead to localized convective activity embedded in monsoon circulation. The observational aspect of the event is demonstrated by the use of satellite and surface observations in addition to the reanalysis datasets. It is also evident that media report of cloudbursts in Uttarakhand does not stand scrutiny of both observed and satellite-derived data. It has been shown that interaction between trough in mid-latitude westerlies penetrating southward over India and monsoon lows triggered incessant rainfall event. To get the dynamical insight of this heavy rainfall event, vertically integrated water vapor transport is evaluated. This paper is organized in the following manner. Brief description of the data and methodology is described in Sect. 2. Results and discussion are presented in Sect. 3. It includes observational aspects of the event, moisture transport analysis and possible dynamical reasons for the incessant rainfall event over Uttarakhand. Summary and conclusion are illustrated in Sect. 4.

2 Data and methodology

India Meteorological Department (IMD) has established a network of 675 Automatic Weather Stations (AWS) across the country (Ranalkar et al. 2014), and network of 1350 Automatic Rain Gauge (ARG) stations is being established. A fairly dense network of AWS and ARG stations is now available in Uttarakhand (see Fig. 2 for network locations) for operational utilization. The hourly and daily rainfall data recorded by these networks have been used in this study. ERA interim dataset is used to describe synoptic features prevalent during the event augmenting rapid advancement of monsoon and interaction of monsoon low with mid-latitude westerlies resulting in localized heavy rainfall over western Himalayan region.

Romatschke and Houze (2011) have demonstrated that convective systems of various types contribute to the precipitation of South Asian monsoon. In particular, they have shown that rain in western Himalayan indentation is almost exclusively convective in nature which occurs from small-sized ($600\text{--}10,000\text{ km}^2$) precipitation system. In order to explore this aspect in Uttarakhand rainfall event of June 14–17, 2013, an area bounded by $29\text{--}32^\circ\text{N}$, $77\text{--}81^\circ\text{E}$ is considered. The evolution and progression of rain band over the region are analyzed using Tropical Rainfall Measuring Mission (TRMM) 3B42 dataset (Kummerow et al. 2000, 1998). Polarization-Corrected Brightness Temperature (PCT) at 85 GHz microwave channel is also used as a proxy for convection. The PCT ($1.818 T_{\text{BV}} - 0.818 T_{\text{BH}}$) was computed following Spencer et al. (1989) using TRMM 1B11 dataset. Here, T_{BV} is brightness temperature for vertically polarized channel at 85 GHz and T_{BH} is brightness temperature for horizontally polarized channel at 85 GHz. A PCT range of 250–260 K is generally taken as threshold below which precipitating systems are found. PCT value of 250 K corresponds to moderate rain rate of 3 mm h^{-1} . Mohr and Zipser (1996) have employed Goddard scattering algorithm and used existence of 225 K PCT to indicate cumulonimbus convection with rain rate of 10 mm h^{-1} . In this study, surface rain rates from TRMM PR (Precipitation Radar) were analyzed using 2A25 dataset for Uttarakhand rainfall event.

In heavy rainfall events, rain rates exceed evaporation rates, and thus, availability of low-level moisture convergence is expected to increase intensity of rainfall (Teixeira and Satyamurty 2007).

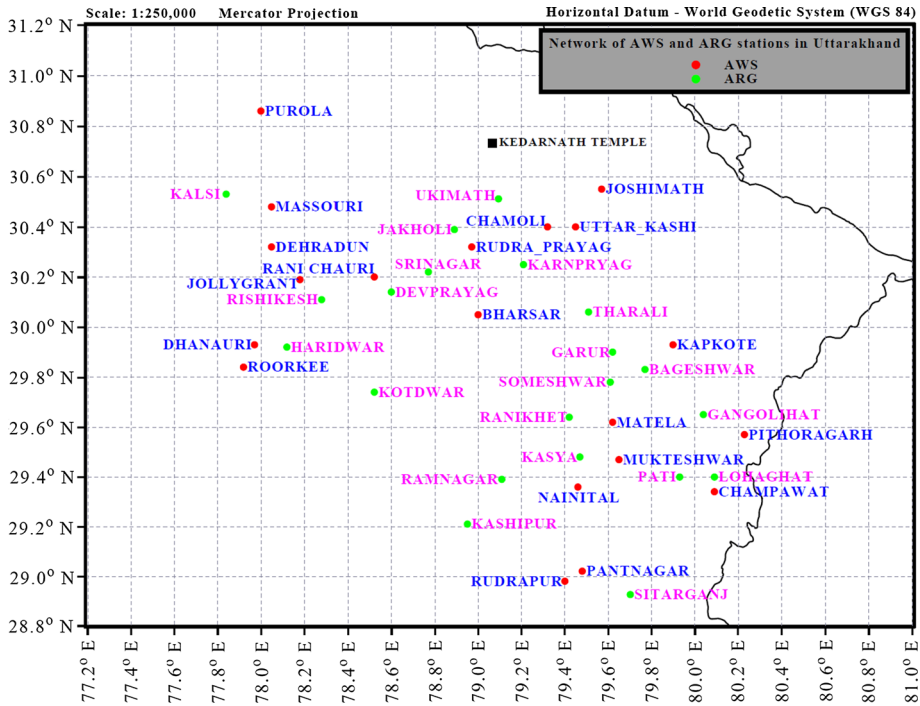


Fig. 2 India Meteorological Department (IMD) network locations of AWS and ARG stations in Uttarakhand region

To explore the dynamical link, moisture transport analysis is presented. The vertically integrated water vapor transport (\vec{Q}) is defined as:

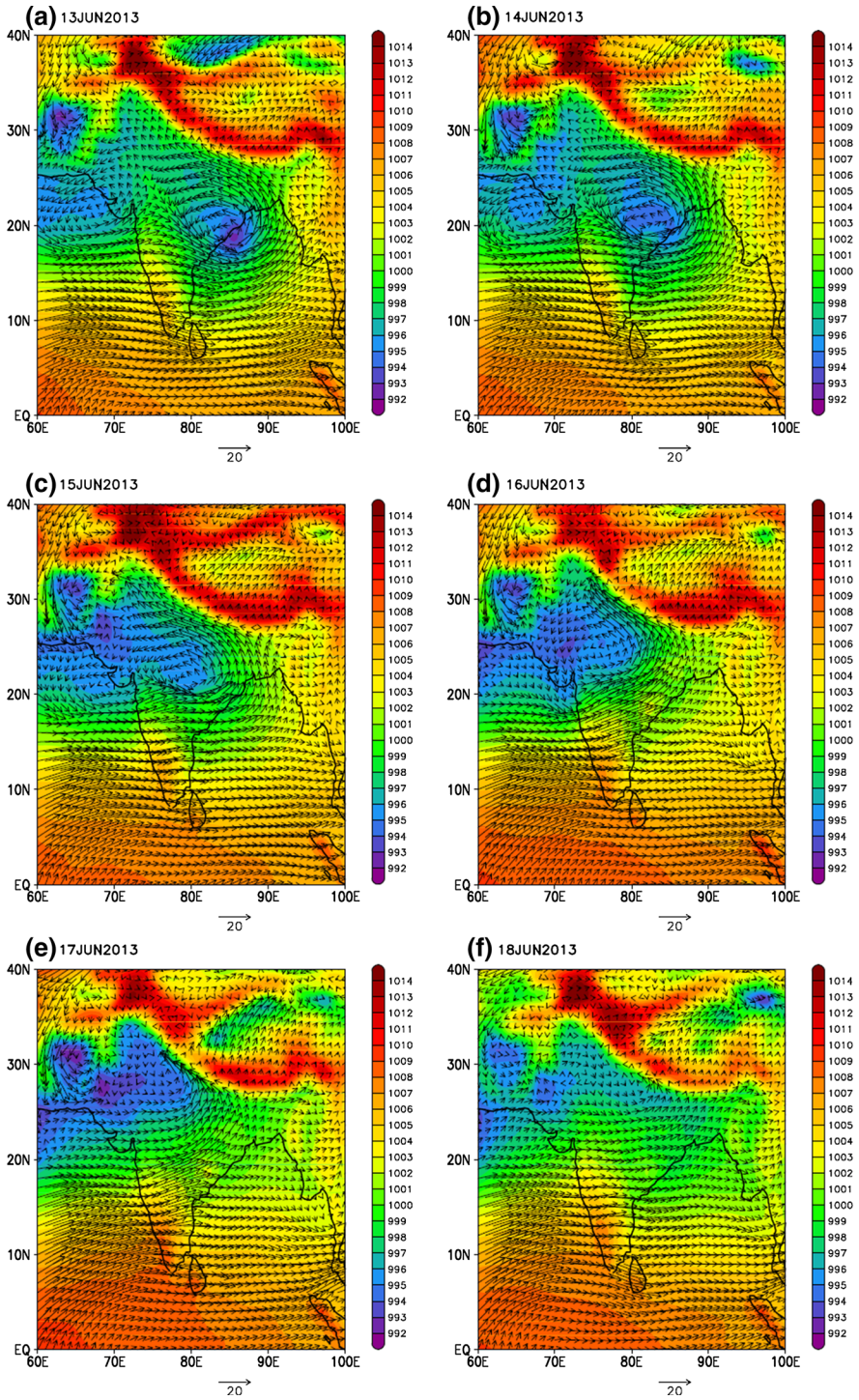
$$\vec{Q} = \frac{1}{g} \int_{P_{300}}^{P_s} q \vec{V} dP$$

where g is the acceleration due to gravity, q is the specific humidity, P_s is surface pressure, P_{300} is pressure at the top of the atmosphere, and \vec{V} is the wind vector (Chen 1985; Rao et al. 2010; Chaudhari et al. 2013). The use of Helmholtz theorem allows us to separate the moisture transport into rotational and irrotational (flux divergence) components. The moisture transport was computed using Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis fields developed by NASA (Rienecker et al. 2011).

3 Results and discussion

3.1 Observational aspects of the Uttarakhand event and prevailing synoptic situation

A brief description of synoptic conditions that prevailed during the event would be useful for further analysis and understanding of mechanism leading to heavy rainfall over the



◀ **Fig. 3** Lower tropospheric (at 850 hPa) wind patterns overlaid on mean sea-level pressure during **a** June 13, 2013, **b** June 14, 2013, **c** June 15, 2013, and **d** June 16, 2013, **e** June 17, 2013, and **f** June 18, 2013 (depicts movement of monsoon low)

Uttarakhand region. According to Indian Daily Weather Reports (IDWR, www.imd.gov.in), monsoon trough passed through Bikaner, Gwalior, Gaya and Imphal and across the Gangetic West Bengal. Low pressure area is originated over northwest Bay of Bengal (Fig. 3a; ERA interim-based mean sea-level pressure and wind patterns at 850 hPa). The monsoon low moved eastwards and was seen over Odisha region on June 13, 2013. The low intensified into a well-marked low pressure area. As shown in Fig. 3b–f, the system sustained its rapid northwestward movement along the monsoon trough till June 18, 2013, and thereafter, it weakened into a cyclonic circulation over Haryana and adjoining west Uttar Pradesh. A western disturbance (WD) in the form of a trough in mid-tropospheric level was observed around west Rajasthan on June 16, 2013. A deep penetration of mid-latitude westerlies at 500 hPa level is occurred (Fig. 4a). This WD moved eastwards (toward east Rajasthan), and it was observed near northern regions of India (Punjab, Haryana, Uttarakhand and adjoining areas) on June 18, 2013, which is shown in Fig. 4b, c. This system finally moved away eastwards on June 19, 2013, as shown in Fig. 4d.

The movement of rain band (averaged over the longitudinal belt 77°E–81°E) during June 12–19, 2013, is depicted in Fig. 5a in the form of Hovmoller diagram. The northward movement of monsoon low from June 12 to 19, 2014, is clearly noted. The topography averaged over the longitudinal belt (averaged over 77°E–81°E) is juxtaposed with the Hovmoller diagram (Fig. 5b). It pinpoints that orography has played a significant role in modulating rainfall over Uttarakhand region. The daily area averaged rainfall during June 12–19, 2013, along with climatology using TRMM TB42 dataset is shown in Fig. 5c. The region experienced nonzero daily rainfall during this period. The rainfall over the region on June 16 and June 17, 2013, was approximately 500–700 % of its climatological normal. The threshold for monsoon surge for most of the days has exceeded climatological normal. On June 16 and June 17, 2013, it exceeded climatological normal by 3 times of SD.

Warm moist air in lower troposphere (Fig. 3) and cold dry mid-latitude air (Fig. 4) interaction occurred over western Himalayan barrier at Uttarakhand. This synoptic condition aided by orographic upliftment (Fig. 5a–c) proved very conducive for localized heavy rainfall activity over the region. Spatial distribution of rainfall from TRMM along with ERA interim lower tropospheric wind patterns (at 850 hPa) during June 13, 2013, to June 18, 2013, is presented in Fig. 6. The movement of rainband along monsoon low (Fig. 6a–c) and heavy rainfall activity centered on Uttarakhand region are evident from Fig. 6c–e. The rainband shifted eastward and rainfall activity was subdued on June 18, 2013, which is clear from Fig. 6f.

The hourly and daily rainfall events are well recorded by AWS and ARG stations during the period June 14–18, 2010. Many stations in the state recorded a rainfall exceeding 200 mm in 5 days as shown in Table 1. The hourly rainfall recorded at Dehradun AWS and Kalsi ARG station from 0300 UTC of June 16, 2013, to 0300 UTC of June 17, 2013, is presented in Fig. 7a, b. Similarly, hourly variation of rainfall recorded at Dhanauri and Ukimath ARG stations from 0300 UTC to 1800 UTC of June 16, 2013, is shown in Fig. 7c, d. It can be concluded from daily and hourly variation of rainfall recorded at AWS and ARG stations that widespread and incessant rainfall occurred at stations in Uttarakhand during the period; however, the rain rate was well below 100 mm h^{-1} , and hence, the event was not a cloudburst.

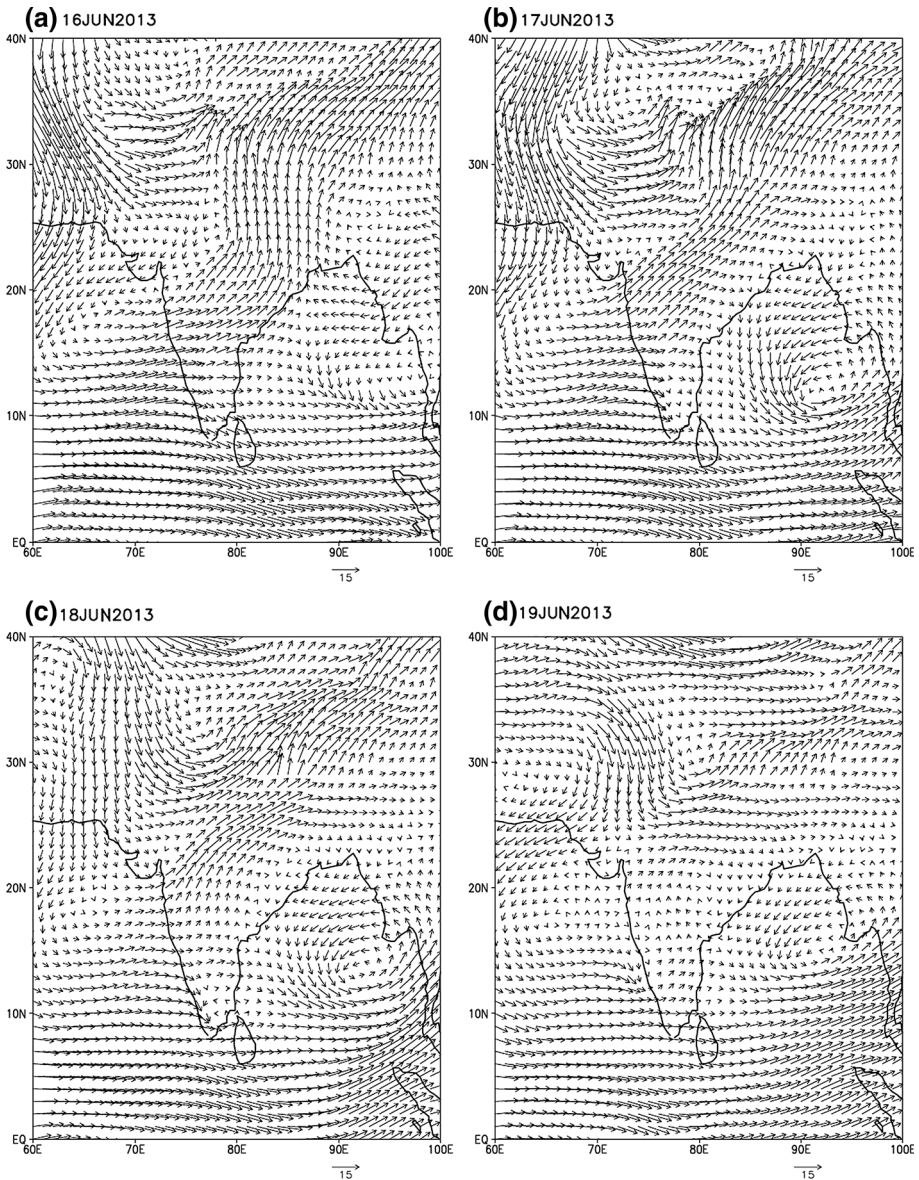


Fig. 4 Mid-tropospheric (at 500 hPa) wind pattern during **a** June 16, 2013, **b** June 17, 2013, **c** June 18, 2013, and **d** June 19, 2013, showing trough over northwest India due to southward penetration of mid-latitude westerlies

3.2 Polarization-corrected temperature (PCT) as convective proxies

The sporadic lightning discharges as seen by Lightning Imaging Sensor (LIS) aboard TRMM satellite during June 14, 2013, to June 17, 2013, are overlaid on topography of the region in Fig. 8. The presence of lightning discharges (see Fig. 8) makes it reasonable to assume that atmosphere was conditionally unstable and favorable for the convection. Many

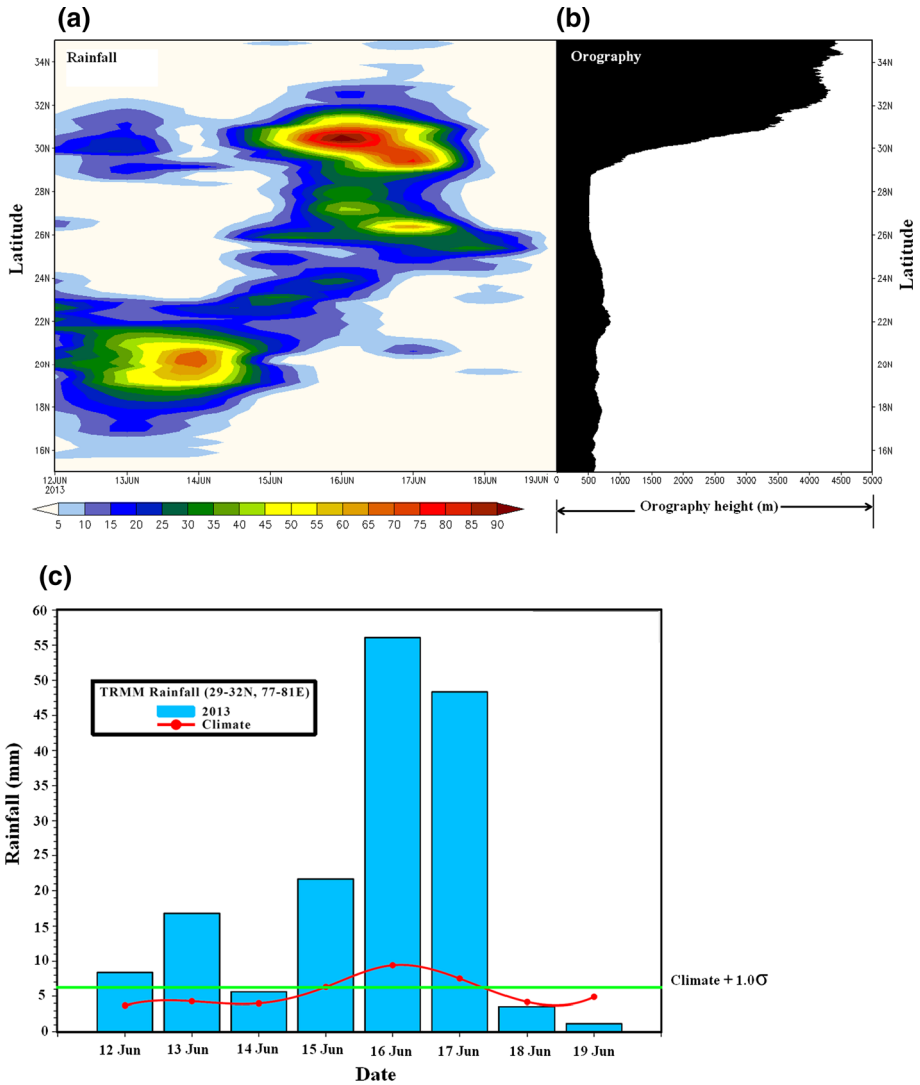
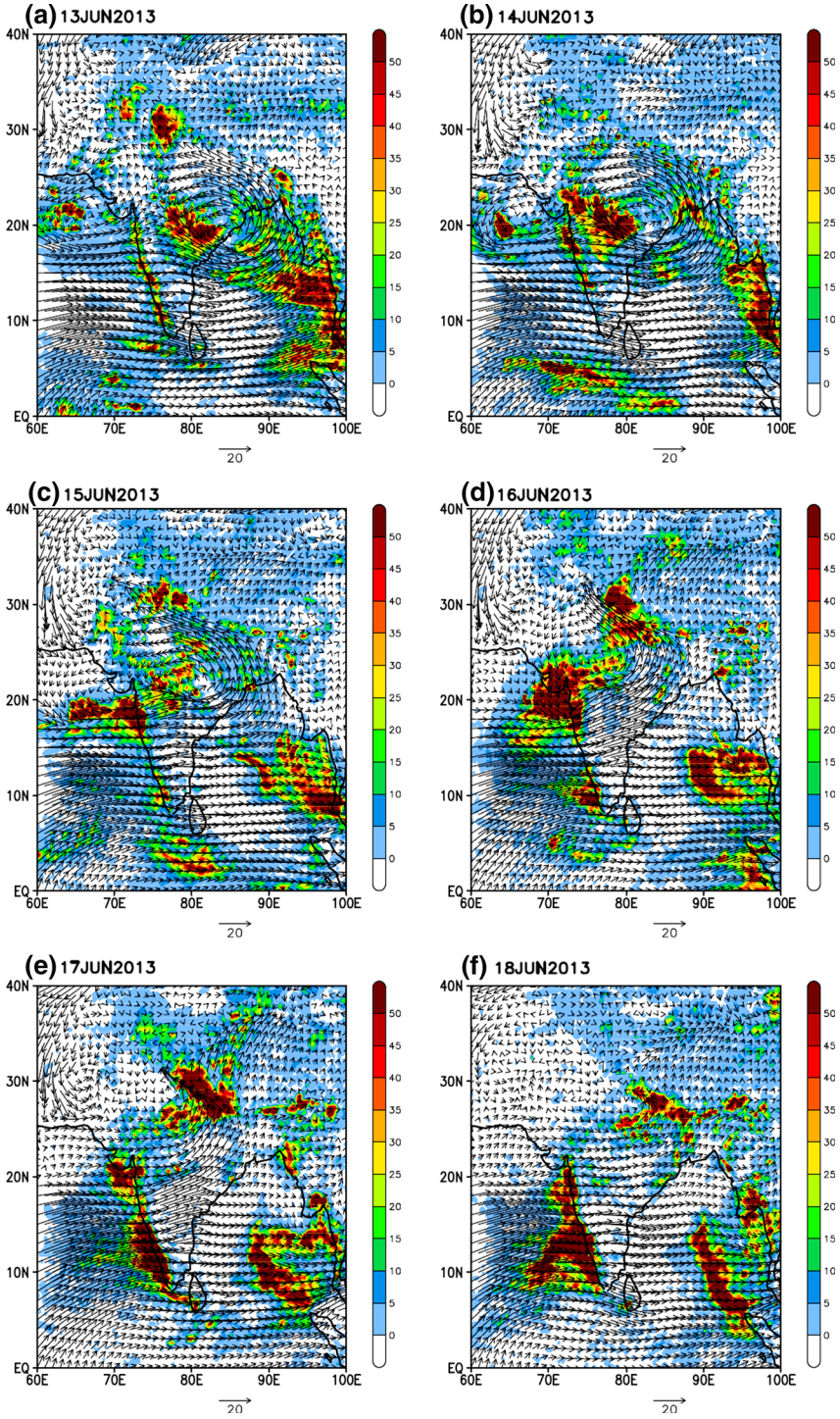


Fig. 5 **a** Time-latitude section of daily rainfall (unit: mm) during June 12–19, 2013 (averaged over 77°E–81°E) depicting monsoon surges. **b** The orography (unit: m) of the region averaged over 77°E–81°E, **c** TRMM TB42 daily area averaged rainfall (unit: mm) during June 12–19, 2013, along with corresponding daily climatology (shown in red color) based on long-term mean (1998–2012)

studies (Todd and Bailey 1995; Nesbitt et al. 2000) have suggested that PCT can be used as convective proxy. Hence, the polarization-corrected temperature (PCT) derived from 85 GHz channel using TRMM 1B11 dataset is utilized in the present analysis. PCT for the period June 15–17, 2013, is presented in Fig. 9. In this figure, the pixels with PCT > 250 K are shaded in gray color and those with PCT < 250 K are shaded in color (as discussed above it is indicative of convection). As local convection and orographic upliftment are expected to cause rainfall from the weather system, the PCT was monitored



◀ **Fig. 6** Variation of daily rainfall (unit: mm) during June 13–18, 2013, as seen by TRMM overlaid on 850 hPa ERA interim wind vectors

Table 1 Daily rainfall (mm) recorded at selected AWS and ARG stations in Uttarakhand

No.	Station name	Lat (°N)	Long (°E)	June 14, 2013	June 15, 2013	June 16, 2013	June 17, 2013	June 18, 2013	Total
1	BHARSAR	30.05	79.00	43	0	145	122	80	390
2	CHAMPAWAT	29.34	80.09	0	1	39	194	222	456
3	DEHRADUN	30.32	78.05	89	54	210	338	9	700
4	DHANAUARI	29.93	77.97	0	17	203	151	11	382
5	JOLLYGRANT	30.19	78.18	43	28	203	224	29	527
6	MATELA	29.62	79.62	9	1	33	97	100	240
7	NAINITAL	29.36	79.46	9	18	62	216	188	493
8	PANTNAGAR	29.02	79.48	0	0	2	58	115	175
9	PITHORAGARH	29.57	80.23	0	0	12	69	123	204
10	RANI_CHAWRI	30.20	78.52	4	2	163	205	47	421
11	ROORKEE	29.84	77.92	0	5	51	148	15	219
12	RAMNAGAR	29.39	79.11	0	1	16	56	58	131
13	RANIKHET	29.64	79.42	1	0	17	43	50	111
14	HARIDWAR	29.92	78.12	10	20	86	218	14	348
15	RISHIKESH	30.11	78.28	16	2	178	145	40	381
16	KALSI	30.53	77.84	20	95	175	391	33	714
17	PATI	29.40	79.93	3	0	82	206	128	419
18	LOHAGHAT	29.40	80.09	2	0	21	139	181	343
19	DEVPRAYAG	30.14	78.60	0	7	129	116	50	302
20	SRINAGAR	30.22	78.77	0	0	129	133	58	320
21	BAGESHWAR	29.83	79.77	15	3	61	161	63	303
22	JAKHOLI	30.39	78.89	25	72	121	108	65	391
23	SITARGANJ	28.93	79.70	0	0	8	75	174	257
24	GANGOLIHAT	29.65	80.04	0	0	24	103	125	252

in the area bounded by 29°N–32°N and 77°E–81°E. The channel is sensitive to precipitation-sized ice particles which scatters the upwelling radiation and reduces the brightness temperature. Thus, low brightness temperature implies increased updraft strength. The stronger updraft produces more supercooled water droplets and hence larger graupels through rimming. The large graupels lead to scattering the upwelling microwave radiation. The low brightness temperature, therefore, also indicates increased latent heat release and precipitation. As the low pressure area moved over central India on June 15, 2013, the PCT at pixels centered on Rudraprayag, Chamoli, Uttar Kashi and Karnaprayag was less than 250 K (see Fig. 9a). Similarly, during second pass of TRMM on June 15, 2013, the pixels west of Dehradun, north of Kedarnath and north of Nainital depicted lower values of PCT at 12:22 UTC (Fig. 9b). Thus, Fig. 9a, b shows indication of rainfall over these regions. First pass of TRMM on June 16, 2013, during 0810 UTC to 0811 UTC as shown in Fig. 9c

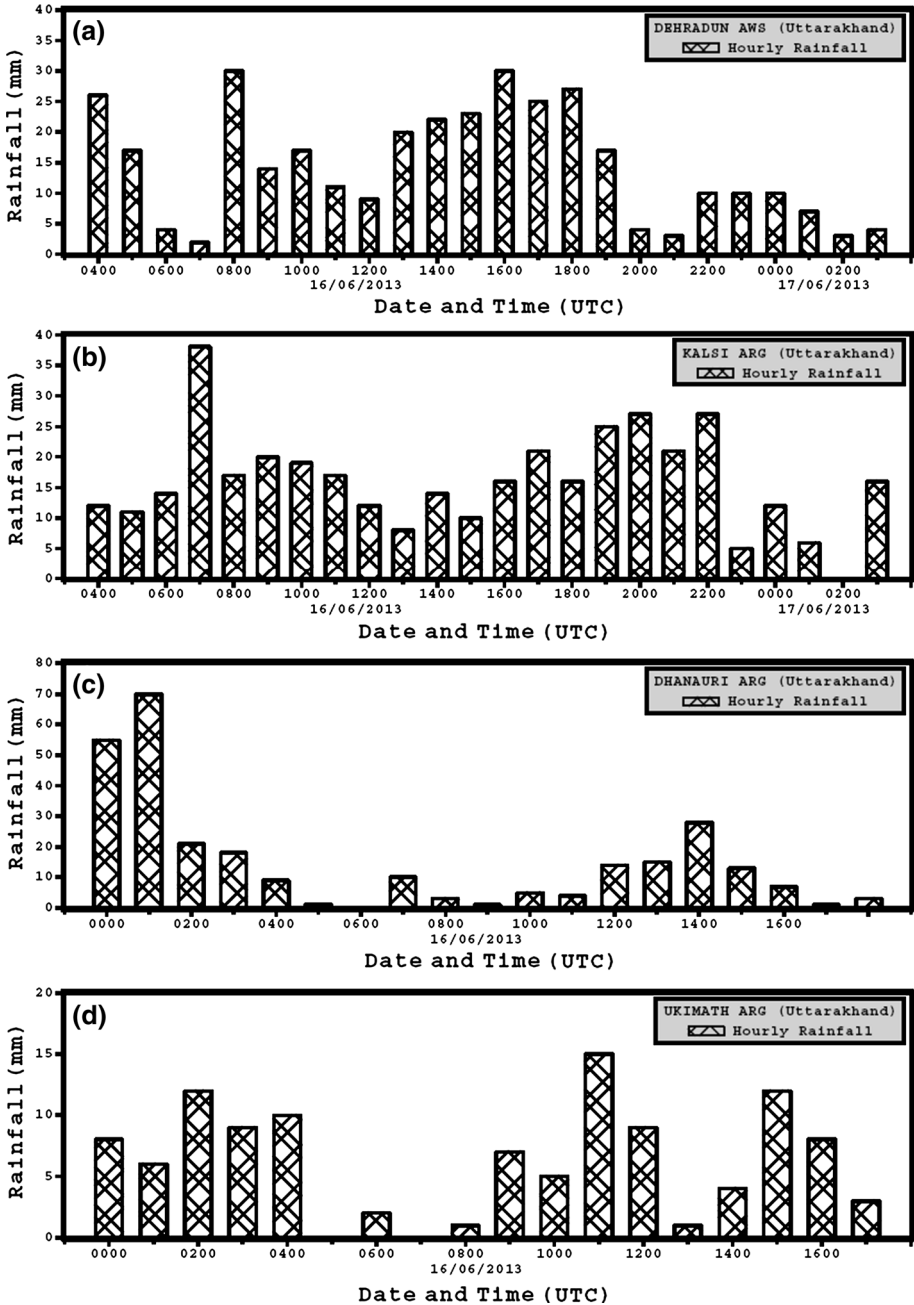


Fig. 7 Hourly rainfall (mm) recorded at AWS and ARG stations in the state of Uttarakhand

depicts large number of pixels (including those over the station Purola, Dehradun, Kalsi, Rani Chauri, Massouri and north of Kedarnath) with PCT well below 250 K. As shown in Fig. 7a, b, Dehradun AWS and Kalsi ARG station recorded significant rainfall during 0700

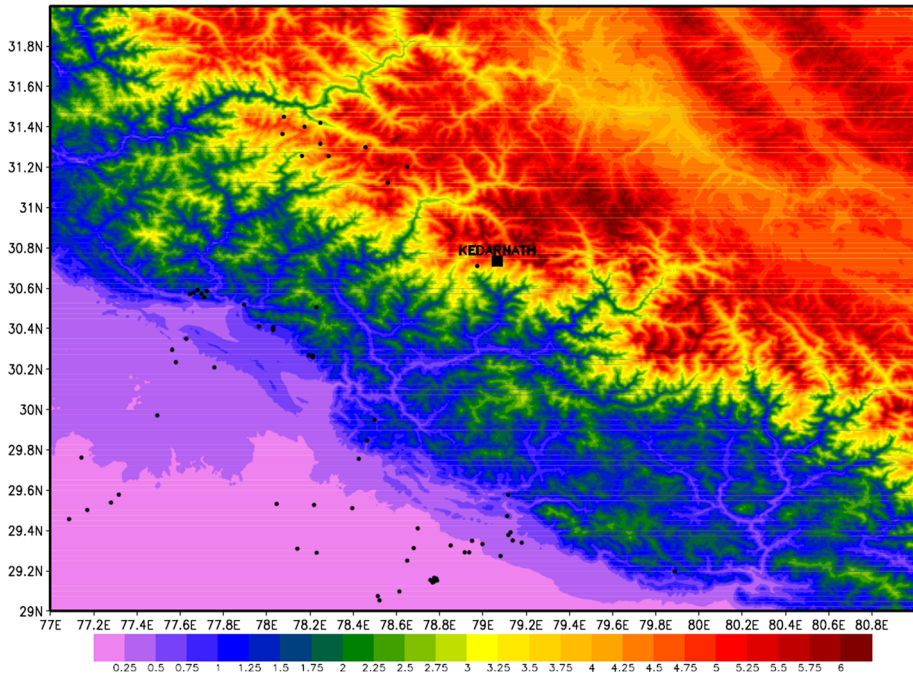


Fig. 8 Orography (km) of the Uttarakhand region (*black dots* indicate lightning strikes recorded by Lightning Imaging Sensor—LIS aboard TRMM)

UTC to 0900 UTC of June 16, 2013. The second pass of TRMM over the region on June 16, 2013, during 1126 UTC to 1127 UTC is shown in Fig. 9d which also depicts PCT below the threshold of 250 K at large number of pixels in upper ranges of the Himalaya. In fact, incessant rainfall occurred at many stations in Uttarakhand on June 16, 2013, due to the passage of the system. Figure 9e, f shows TRMM passes over the region on June 17, 2013. The pixels with PCT < 250 K indicate passage of convective system over Kedar-nath, Ukimath, Joshimath, Chamoli, Jakholi, Rudraprayag, Devprayag, Karnaprayag, etc. The hourly rainfall recorded at two representative ARG stations Jakoli and Devprayag is presented in Fig. 10a, b. It can be seen that both stations experienced rainfall till 1100 UTC of June 17, 2013, and thereafter, rainfall activity ceased. This is in conformity with Fig. 9f which shows trailing pixels with PCT > 250 K. A snapshot taken by Precipitation Radar aboard TRMM on June 17, 2013, is shown in Fig. 11, which indicates that region experienced rain rate of the order of 6–20 mm h⁻¹. The rain rate exceeding 40 mm h⁻¹ is recorded at a few pixels; however, none of the pixels had value in excess of 100 mm h⁻¹, which again verifies that Uttarakhand event was not because of cloudburst.

3.3 Moisture transport and intrusion of mid-latitude westerlies over Uttarakhand region

To gain further dynamical insight into the dynamical mechanism of rainfall activity over Uttarakhand region, we have calculated vertically integrated water vapor transport over the Indian region and surrounding oceanic region. The divergent component of moisture

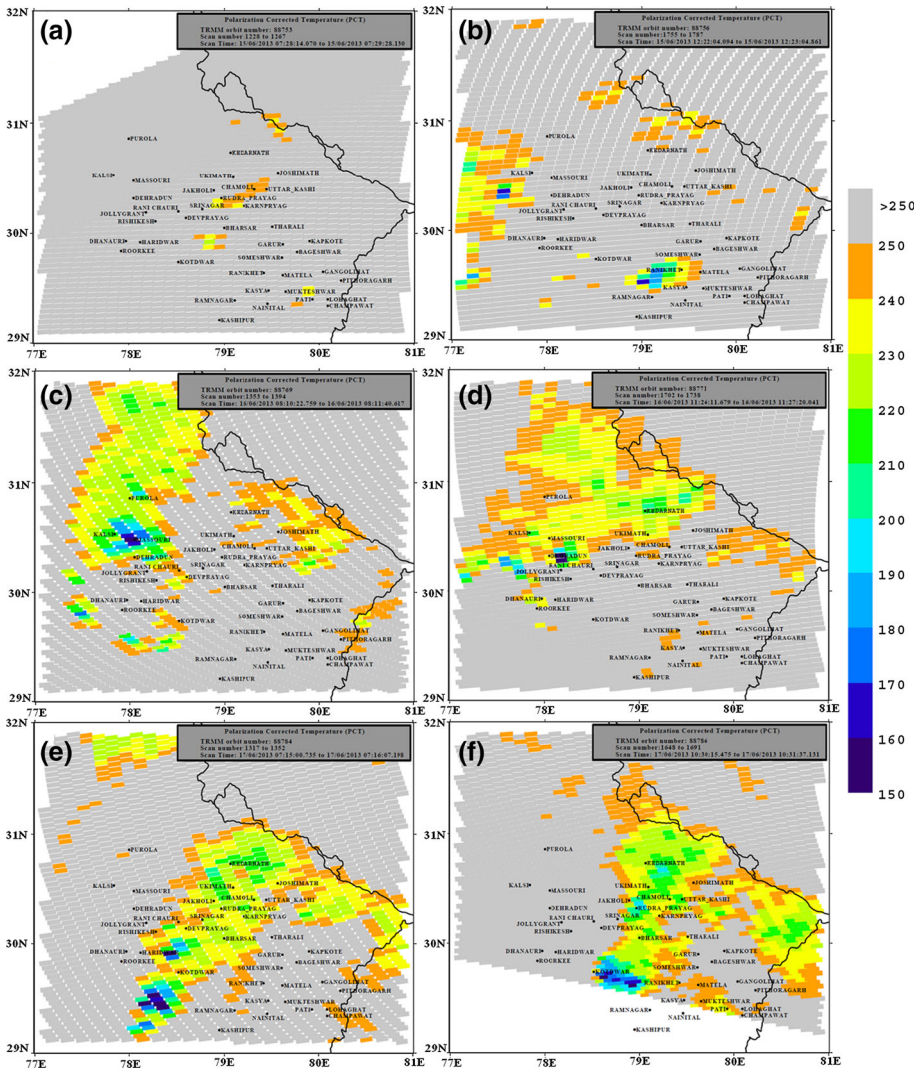


Fig. 9 Polarization-corrected temperature (PCT) over Uttarakhand from June 15, 2013, to June 17, 2013, for daily two TRMM overpasses (PCT < 250 K are shaded in color to indicate conditions favorable for convection)

transport and associated divergent wind vectors are presented in Fig. 12. On June 14, 2013, strong moisture divergence has taken place from the Mascarene high and moisture convergence is seen over Indian region, and it has spatial extent up to head Bay of Bengal (Fig. 12a). This moisture convergence is strengthened further on June 15 and June 16, 2013, by influx of more moisture from Arabian Sea and Bay of Bengal region (Fig. 12b, c, strong moisture convergence region is marked by circle). The moisture convergence weakened on June 17, 2013 (Fig. 12d). This is clear from deviation of divergent component of moisture transport on June 15, 2013, June 16, 2013, and June 17, 2013, from that of June 14, 2013, presented in Fig. 13a–c with mean respective moisture transport vectors

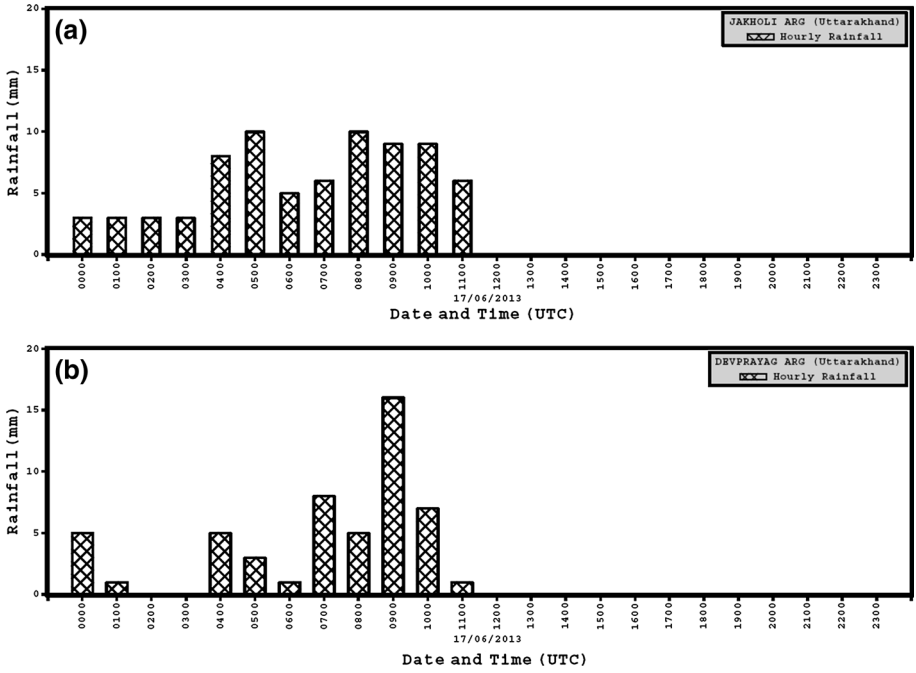


Fig. 10 Hourly rainfall (mm) recorded at Jakholi and Devprayag ARG stations

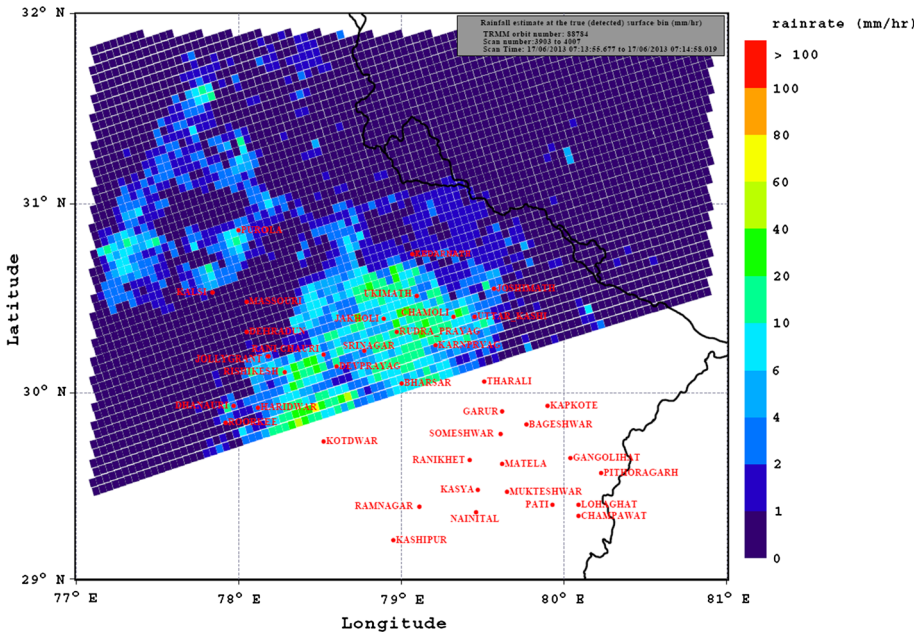


Fig. 11 Rain rate (mm/h) as estimated by TRMM Precipitation Radar on June 17, 2013, as it passed over Uttarakhand

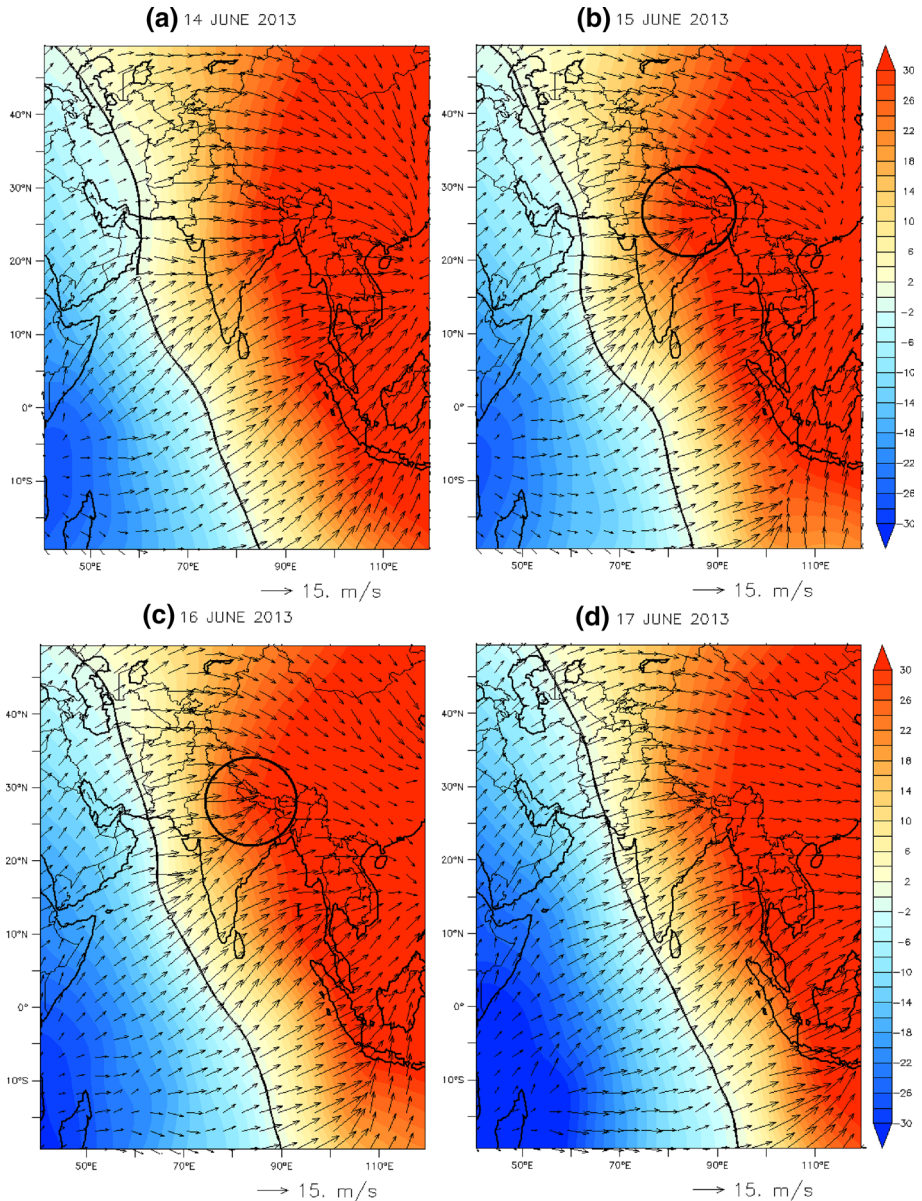


Fig. 12 Divergent component of moisture transport ($\text{kg s}^{-1} \text{m}^{-1}$) represented (shown in *shaded region*) and related moisture transport vectors on **a** June 14, 2013, **b** June 15, 2013, **c** June 16, 2013, and **d** June 17, 2013

superimposed. Figure 13a (for June 15, 2013) depicts strong moisture convergence over Uttarakhand region by influx of moisture from Arabian Sea and Bay of Bengal region. The moisture is trapped over Uttarakhand region on June 16, 2013 (Fig. 13b). Monsoon low movement along with additional influx from Arabian Sea might have further triggered

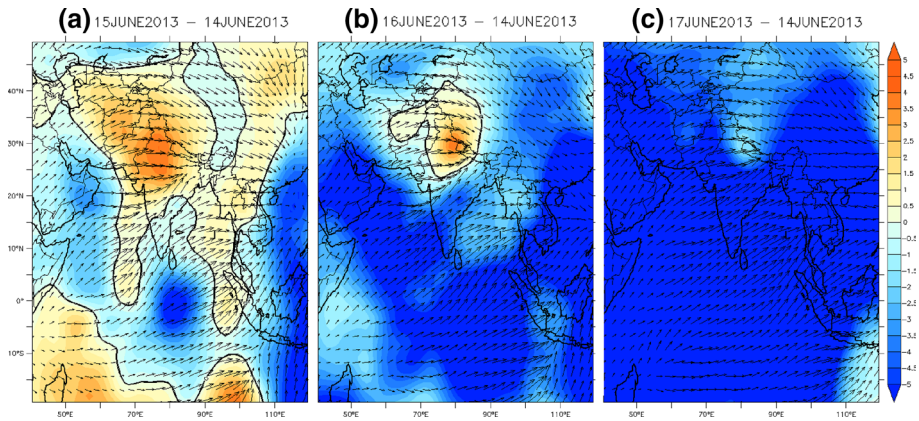


Fig. 13 Deviation of divergent component of moisture transport (unit: $\text{kg s}^{-1} \text{m}^{-1}$; shown in shaded region) on **a** June 15, 2013, **b** June 16, 2013, and **c** June 17, 2013, with respect to that of June 14, 2013. Mean respective moisture transport vectors are superimposed

rainfall activity over the region. Mid-latitude westerlies penetrated Southward over Indian region up to 20°N is during June 14–17, 2013 (Fig. 14a–d). It can also be inferred from Figs. 6 and 14 that there was constant feeding of moisture from both Arabian Sea and Bay of Bengal in the lower level. It resulted in increased moisture transport leading to strong low-level convergence. In upper level, there is mid-latitude westerly trough (Fig. 14) which indicates strong upper-level divergence (ahead of trough). These lower-level convergence and upper-level divergence lead to intensification of the system at surface and resulted in heavy rainfall over Uttarakhand region. The circulation features adjacent to the Caspian Sea could also have an impact on summer monsoon rainfall over northern parts of India (Kriplani et al. 1997). These features are also evident from Fig. 14.

4 Possible reasons for the incessant rainfall event over Uttarakhand

4.1 The mechanism

Upper tropospheric wind patterns (Fig. 14; at 200 hPa) reveal that low index cycle was prevailing during this period (June 14–17, 2013) in which westerlies are weak and maximum belt of westerlies is displaced toward subtropics with wind fields oriented more in meridional direction. Rossby wave pattern is seen in mid-latitudes (Figs. 15, 16). From Fig. 14, it can be concluded that ahead of the trough in westerlies wind speed increases leading to velocity divergence. As discussed earlier, the upper and mid-tropospheric divergence implies convergence in lower troposphere and it is favorable for weather development. It unleashed incessant rainfall over Uttarakhand during June 14–17, 2013.

The anomaly of geopotential height averaged over June 14–17, 2013, is presented in Fig. 15 along with wind speed. The Rossby wave trains characterized by alternate anti-cyclonic and cyclonic anomaly of geopotential height at 200 hPa are seen over Middle East Asia, Pakistan, northern India and South China. The equator-ward flow on eastern side of anticyclone brought cooler and drier air over Middle East Asia. This intrusion of large-scale cold polar air behind the Rossby wave trough further led to the growth and

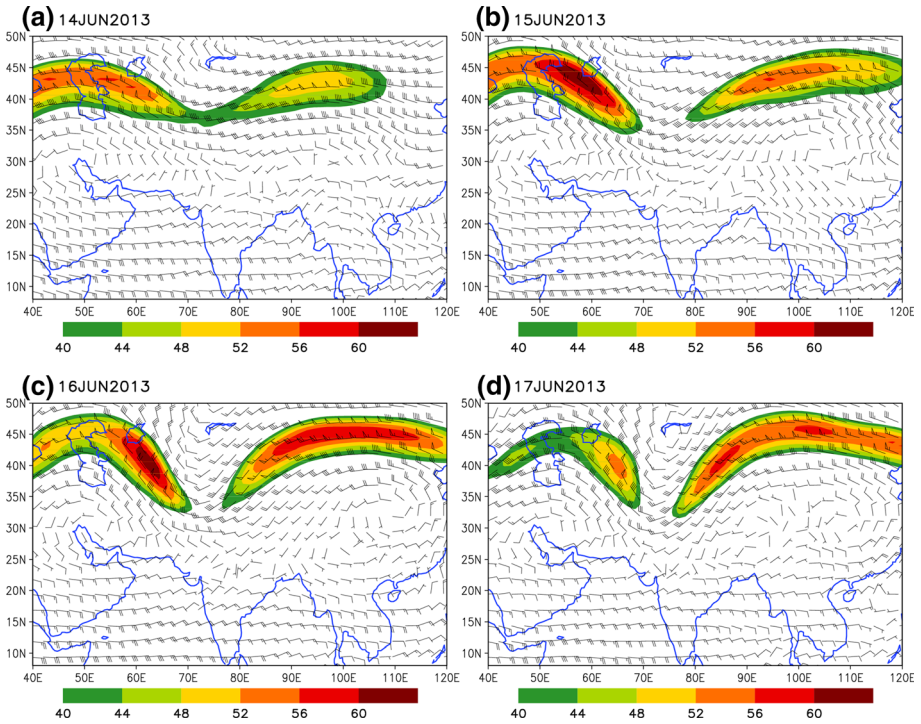


Fig. 14 Upper tropospheric (at 200 hPa) wind patterns during **a** June 14, 2013, **b** June 15, 2013, **c** June 16, 2013, and **d** June 17, 2013 (magnitude of wind speed greater than 40 m/s is marked by shading)

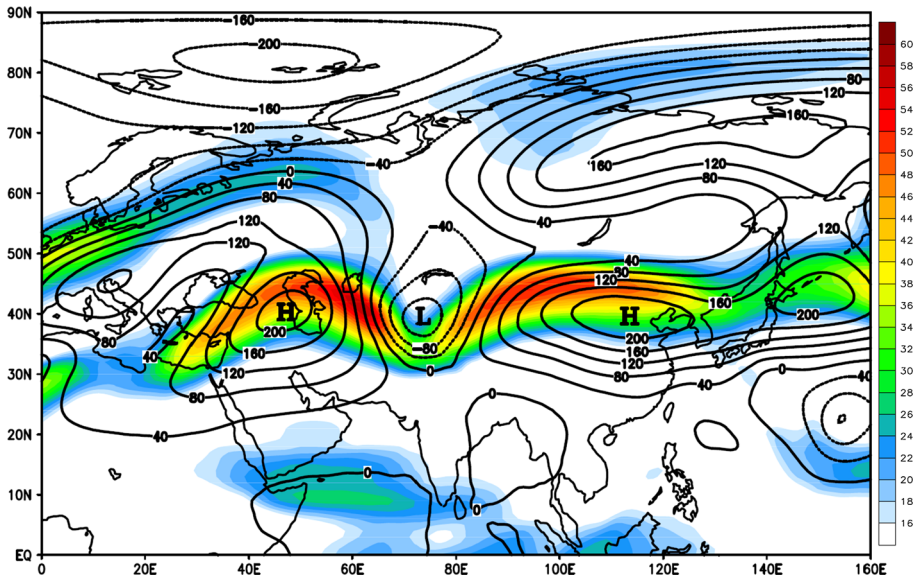


Fig. 15 Anomaly of geopotential height (averaged over June 14–17, 2013) at 200 hPa (contour lines) along with wind speed (averaged over June 14–17, 2013)

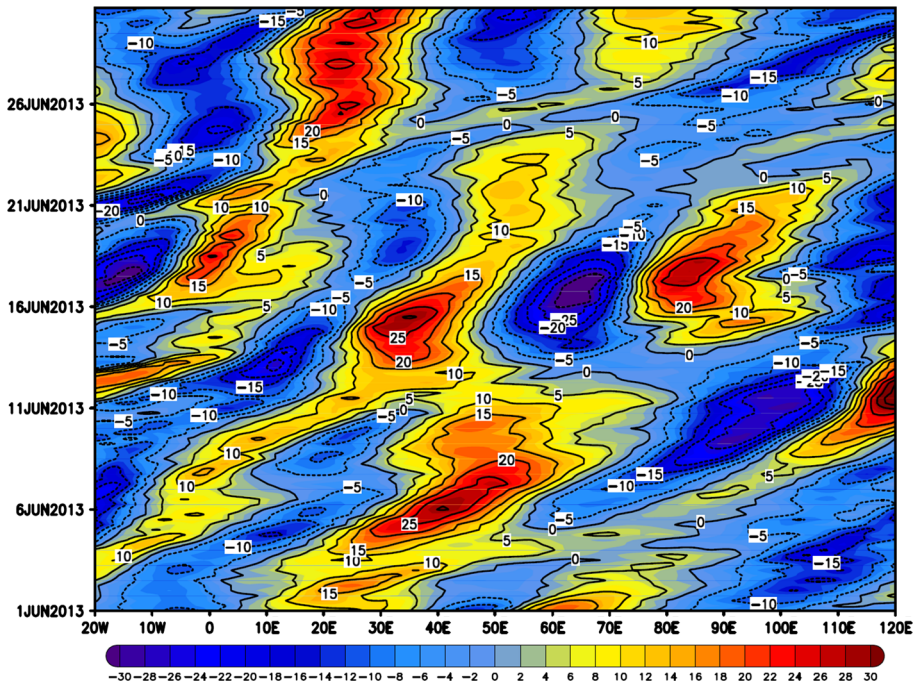


Fig. 16 Hovmöller diagram of meridional wind component during June 2013 averaged over 30°N–50°N

amplification of trough. Similar Rossby wave conditions were noted by Lau and Kim (2012) during 2010 Pakistan flood. Upper air divergence in the left exit and right entrance sectors of subtropical westerly jet (SWJ) are associated with high-speed centers along a jet axis. The monsoon low at the foothill of western Himalayan region was associated with warm moist southeasterly wind flow from the Bay of Bengal and southwesterly wind flow from the Arabian Sea (see Fig. 3). The flow resulted in convergence of moisture over the western Himalaya. As discussed, the lower-level convergence and upper-level divergence are favorable for the convective activity. Figure 16 depicts Hovmöller diagram of meridional wind component averaged over 30°N–50°N latitudinal belt for the month of June 2013. Progression of Rossby wave trains starting from June 12, 2013, is seen at the latitude of 30–50°N (Figs. 16, 15). The strong northerly component along the longitudes 60°E–70°E during 14–17 June (see Fig. 16) implies deep penetration of mid-latitude westerly trough. Intrusion of the large-scale cold polar air (the equator-ward flow on eastern side of anticyclone brought cooler and drier air over Middle East Asia; Fig. 15) behind the Rossby wave trough further leads to the growth and amplification of trough. The trough was embedded within two anticyclones which resulted in its amplification due to advection of curvature positive vorticity (Fig. 17). There is advection of vorticity from trough region (positive curvature vorticity) to velocity divergence region (negative curvature vorticity) and high kinetic energy field (Fig. 17). The westerlies (Fig. 14) draw energy from internal and potential energy stored in zonal current owing to upstream and downstream flow in successive anticyclonic and cyclonic flow (Fig. 15), and termination process occurs with non-availability of potential energy when zonal component becomes insignificant and meridional component dominates (Figs. 14, 16). As a result, sensible heat

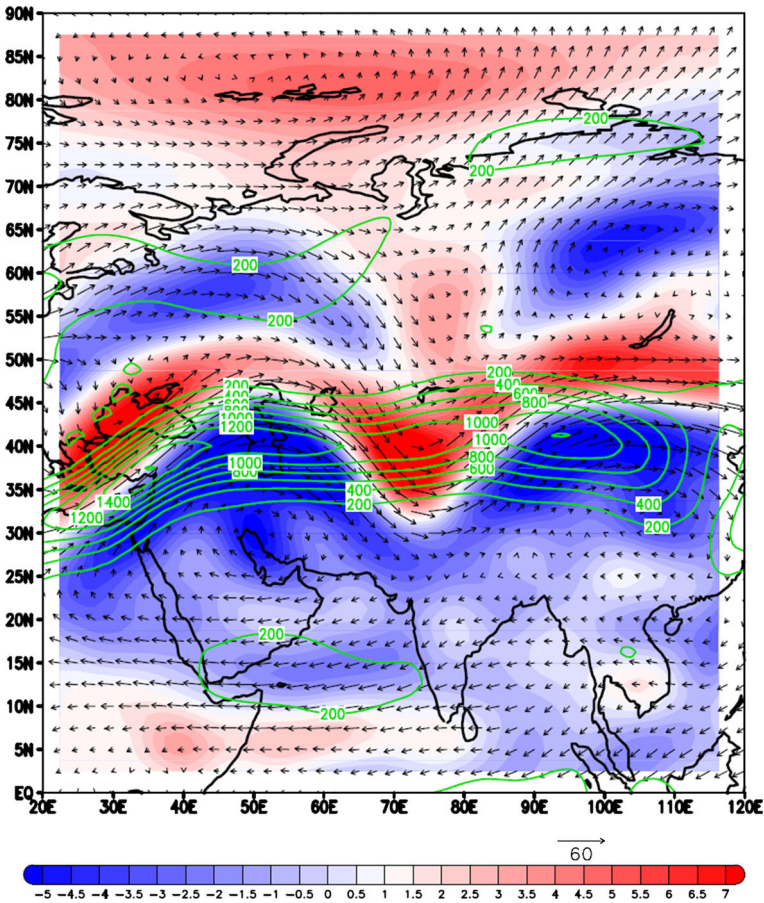


Fig. 17 NCEP reanalysis-2 based curvature vorticity (multiplied by 10^5 ; unit: s^{-1} ; represented by shading) along with kinetic energy (m^2/s^2) and wind vectors at 200 hPa averaged over 14–17 June 2013

is transported across latitudinal trough (Fig. 18a–f; especially on 16 and 17 June), which also indicates availability of moisture over the Uttarakhand region, and this occurs in quasi-periodic manner which has same period as that of index cycle. In this way, Uttarakhand event was culmination of interaction of monsoon trough and intrusion of mid-tropospheric westerlies in Indian latitudes.

5 Summary and conclusion

Observational facets of the heavy rainfall event of Uttarakhand are investigated with the help of observations, reanalysis and satellite datasets. Dynamical mechanism of this event is also presented in this study. Synoptic features are also explored along with role of Himalayan terrain which leads to localized convective activity embedded in monsoon circulation. Results reveal that prevalent synoptic features led to moisture flux convergence in lower troposphere and ultimately culminated in incessant rainfall over Uttarakhand.

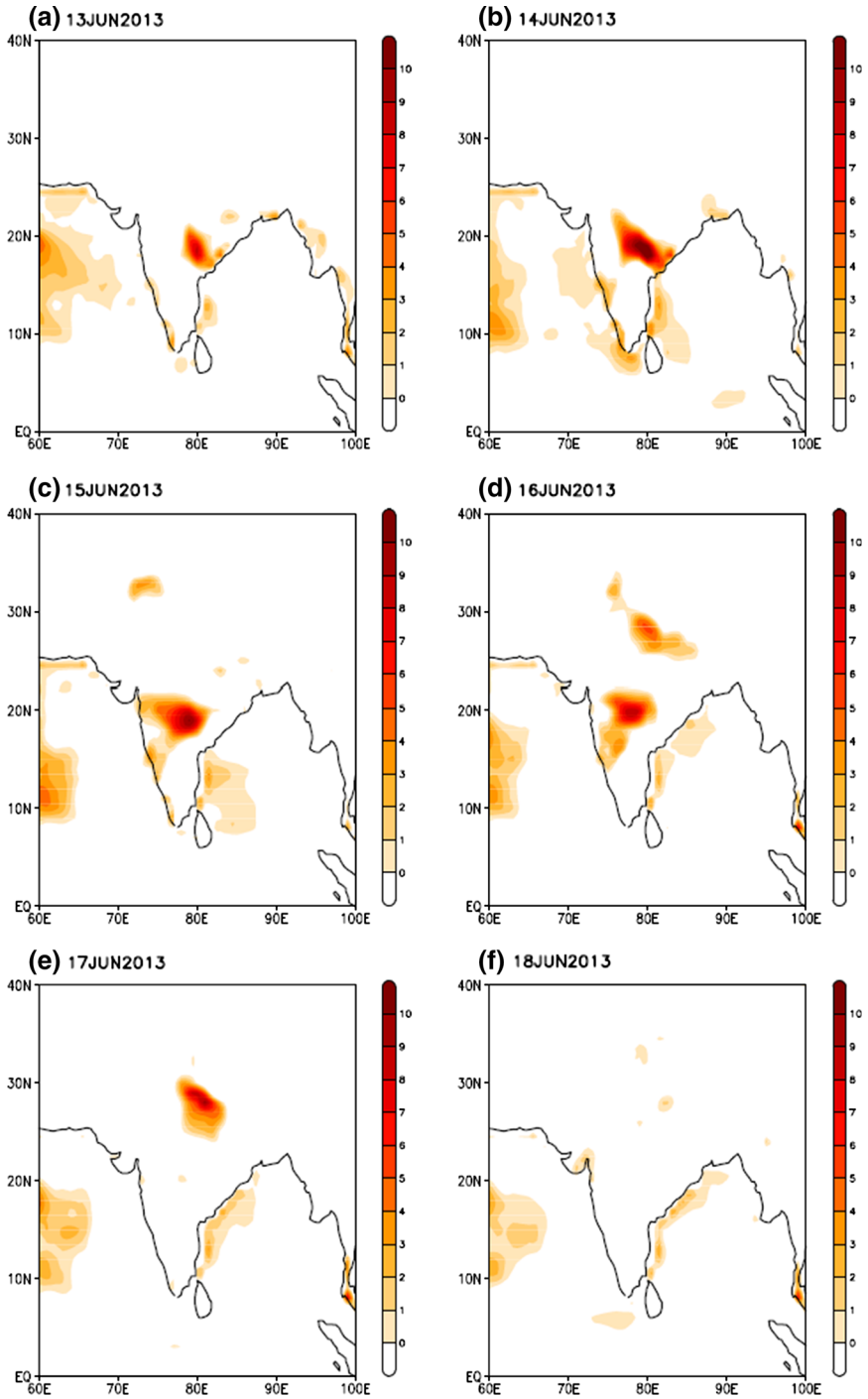


Fig. 18 ERA interim-based surface sensible heat flux (multiplied by 10^{-5} ; Unit: J/m^2) for June 13 and June 18, 2013 (a–f)

Precipitation features have been examined using Precipitation Radar (PR), Automatic Weather Station (AWS) and Automatic Rain Gauge (ARG) station datasets. Additionally, polarization-corrected temperature (PCT) is employed as convective proxies.

To acquire dynamical perspective into the mechanism of this incessant rainfall activity over Uttarakhand region, we have examined vertically integrated water vapor transport over the larger part of Indian region. Strong moisture convergence over Indian region is seen on June 15 and June 16, 2013, by influx of copious moisture from Arabian Sea and Bay of Bengal region. Results connote that moisture is trapped over Uttarakhand region on June 16, 2013. Monsoon low movement along with additional influx from Arabian Sea might have further triggered rainfall activity over the region.

Upper tropospheric wind patterns (at 200 hPa) depict a prevailing low index cycle in which westerlies were weak and maximum belt of westerlies is displaced toward subtropics with wind field oriented in the meridional direction. Rossby wave pattern is seen in mid-latitudes. The ahead of the trough, in westerlies, wind speed increases leading to velocity divergence. The upper and mid-tropospheric divergence implies convergence in lower troposphere, and it is favorable for weather development. It further resulted in heavy rainfall over Uttarakhand during June 14–17, 2014. Thus, this event was a culmination of interaction of monsoon trough and intrusion of mid-tropospheric westerlies in Indian latitudes.

Dynamical processes have leading role in this heavy rainfall event. Additionally, landslides and flood (which are known corollaries of incessant rainfall in the fragile Himalayan terrain) might have increased the catastrophic loss of life and property.

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