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A case study of exceptionally heavy rainfall event over Uttarakhand, India on 18th October, 2021 and its forecasting

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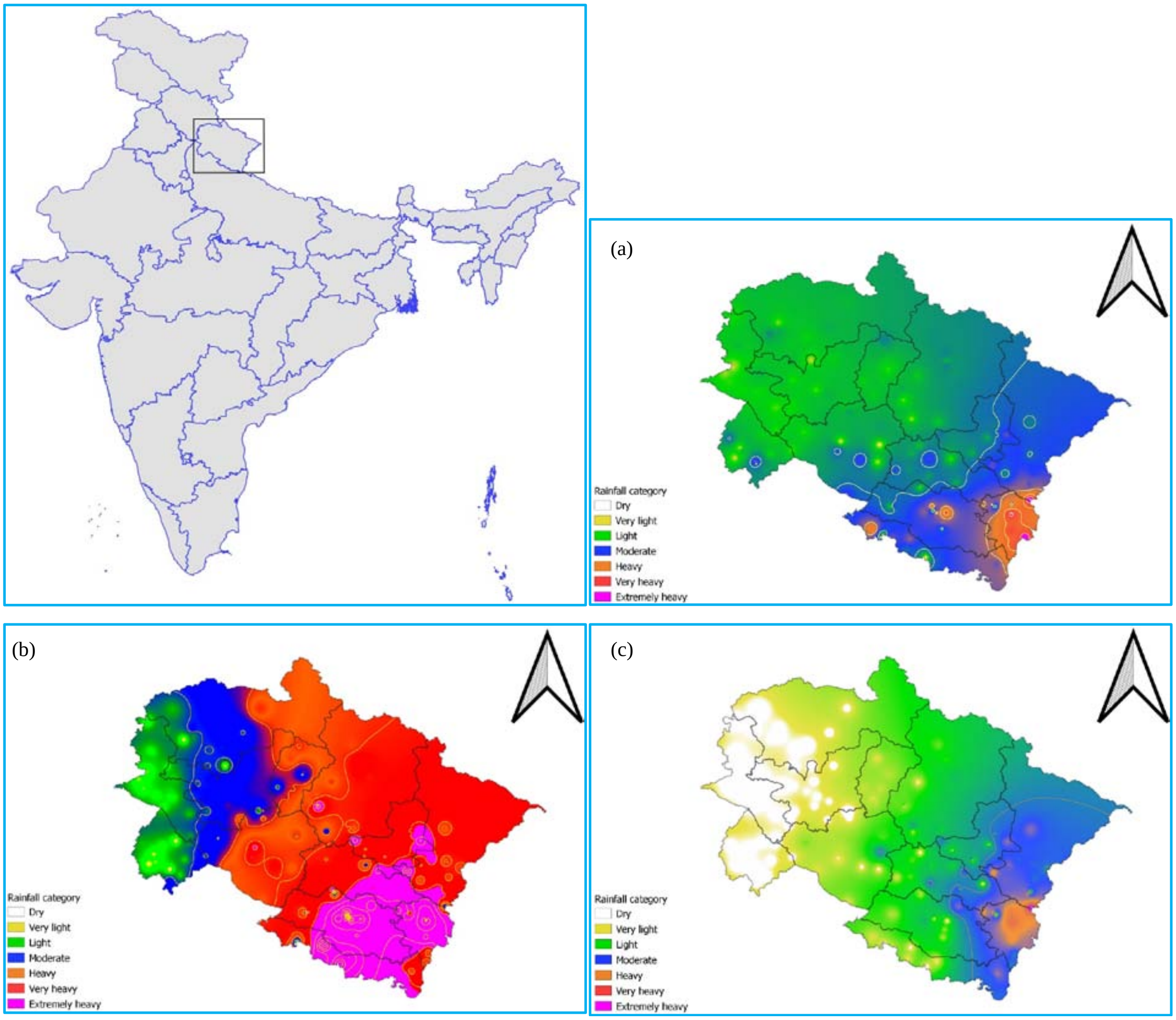
सार — **उत्तराखंड में** 18 **अक्टूबर** 2021 **को हुई अप्रत्याशित वर्षा के कारण उत्तराखंड के कुमाऊं क्षेत्र और गढ़वाल क्षेत्र के आस-पास के जिलों में भूस्खलन, मलबे का प्रवाह और बाढ़ आई, जिसके परिणामस्वरूप जन जीवन, कृषि, परिवहन, पर्यटन और अन्य क्षेत्रों को भारी नुकसान हुआ। वर्तमान परिघटना के सिनॉप्टिक और गत्यात्मक अध्ययन से मध्य भारत के ऊपर निम्न-दाब क्षेत्र की गति का पता चला है, जिसके परिणामस्वरूप** 17 **से** 19 **अक्टूबर तक बंगाल की खाड़ी से भारत के गांगेय क्षेत्र में तेज दक्षिण-पूर्वी हवाएँ** (**एटमॉस्फेरिक रिवर**) **चलीं। पूर्व की ओर बढ़ते पश्चिमी विक्षोभ** (WD) **के गहन द्रोणी द्वारा एटमॉस्फेरिक रिवर के संपर्क और अवरोधन के कारण उत्तराखंड में अत्यधिक वर्षा हुई। हालांकि,एक्स-बैंड डॉपलर मौसम रेडार और** 123 **स्वचालित मौसम/वर्षामापी स्टेशनों के आंकड़े बताते हैं कि अधिकांश क्षेत्र में और अधिकांश समय प्रति घंटा वर्षा की दर हल्की से मध्यम तीव्रता** (10-20 **मिमी/घंटा**) **की थी। उधम सिंह नगर, चंपावत, नैनीताल और पौड़ी जिलों के** 7 **स्टेशनों में लगभग** 1 **घंटे की अवधि के लिए वर्षा की दर अत्यंत तीव्र** (50-100 **मीटर/घंटा**) **थी। उत्तराखंड में जून** 2013 **की अत्यधिक भारी वर्षा की परिघटना, जिसने पूरे उत्तराखंड राज्य को प्रभावित किया, के विपरीत वर्तमान परिघटना कुमाऊं क्षेत्र पर केंद्रित थी और उत्तराखंड के कुमाऊं क्षेत्र में** 18 **अक्टूबर**, 2021 **को** 24 **घंटे में अब तक की सबसे अधिक वर्षा देखी गई। सिनॉप्टिक विश्लेषण और** NWP **मॉडल मार्गदर्शन के आधार पर अच्छी सटीकता के साथ उत्तराखंड में संभावित वर्षा और इस परिघटना के प्रभाव का पूर्वानुमान** 5 **दिन पहले ही कर दिया गया था। इस अत्यधिक वर्षा की परिघटना के लिए** IMD-GFS (T-1534) NWP **मॉडल से** 10 **दिनों तक का पूर्वानुमान दिया गया।**

ABSTRACT. The unprecedented rainfall observed over Uttarakhand on 18th October, 2021 caused landslides, debris flow and floods over the Kumaun region and adjoining districts of the Garhwal region of Uttarakhand, which resulted in huge damage to life, agriculture, transport, tourism and other sectors. The synoptic and dynamic study of the current event showed the movement of the Low-Pressure Area over central India resulting in the strong southeasterly winds (Atmospheric River) over Indo-Gangetic planes from the Bay of Bengal from 17th to 19th October. The interaction and blocking of the Atmospheric River by the deep trough of eastward-moving Western Disturbance (WD) caused extreme rainfall over Uttarakhand. However, the X-band Doppler Weather Radar and 123 Automatic Weather/raingauge Stations data suggest that the hourly rainfall rate was of light to moderate intensity (10-20 mm/h) over most of the area and at most of the time. The rainfall rate was extremely intense (50-100 mm/hour) for around 1-hour duration in 7 stations of Udham Singh Nagar, Champawat, Nainital and Pauri districts. Unlike the June 2013 extremely heavy rainfall event over Uttarakhand which impacted the whole Uttarakhand state, the present event was concentrated over the Kumaun region and the highest ever 24-hours accumulated rainfall was observed on 18th October, 2021 in Kumaon region of Uttarakhand. The expected rainfall as well as the impact of the event over Uttarakhand was forecasted 5 days in advance with good accuracy based on the synoptic analysis and NWP model guidance. The predictability of the IMD-GFS (T-1534) NWP model was found to be up to 10 days for this extreme rainfall event.

Key words – Exceptionally heavy rainfall, Mid-level westerly trough, Atmospheric river, Himalayan rainfall forecasting, NWP model.

1. Introduction

The normal date of withdrawal of the southwest monsoon from Uttarakhand is 28th September [Pai *et al.*, 2020]. In the year 2021, the monsoon withdrew from the entire state of Uttarakhand on 8th October, 2021 due to the establishment of an anti-cyclonic circulation in the lower tropospheric levels over northwest India and substantial reduction in moisture content & rainfall. The weather remained dry over Uttarakhand after the withdrawal of the southwest monsoon till 15th October, 2021. The heavy to extremely heavy rainfall event occurred over Uttarakhand



Figs. 1(a-c). 24-hour accumulated observed rainfall for (a) 17th October (b) 18th October and (c) 19th October. The isohyets are drawn at the interval of 50 mm

from 17th to 19th October, 2021 with the peak rainfall activity on 18th October, 2021. The severity of this extreme weather event was highest over Uttarakhand state however, its medium effect was also observed over northwest Indian states of Himachal Pradesh and Uttar Pradesh. The heavy rainfall activity and thus damages were highest over the Kumaun region and adjoining districts of the Garhwal region of Uttarakhand. The most severely affected districts due to exceptionally heavy rainfall were Nainital, Champawat, Udham Singh (US) Nagar and Almora. Fig. 1 shows the observed 24-hour accumulated rainfall over Uttarakhand from 17th to 19th October. Heavy to exceptionally heavy [ADGM(R), 2015] rainfall occurred at most places in the Kumaun region on 18th October. However, the Garhwal region received light to moderate rainfall at most places with isolated heavy to very heavy rainfall in Tehri & Uttarkashi districts on 18th October. Light to moderate rainfall occurred at most places with heavy to extremely heavy rainfall at isolated places in Uttarakhand on 17th October. Light to moderate rainfall also occurred at a few places in the Garhwal region and at most places with heavy to very heavy rainfall at isolated places in the Kumaun region on 19th October. The occurrence of very heavy to extremely heavy rainfall is not unusual in the month of October. A study [Nandargi *et al.*, 2016] of more than 100 years of extreme rainfall events and severe rainstorms over Uttarakhand showed that the maximum frequency of extreme 1-day rainfall (≥100 mm) was recorded in the month of October and the stations at higher altitudes recorded extreme rainfall during October. A study of extreme rainstorms over the Northwest Himalayas from

TABLE 1(a)

Old and new recorded highest 24-hour accumulated rainfall of IMD's stations of Kumaun region. (b) Significant rainfall (>400 mm) observed in 24 hours over other stations in Kumaun region of Uttarakhand

(a)

Station	Date of establishment of observatory/No. of years of data	Old record of 24-hour accumulated rainfall in mm and date of occurrence	Observed 24 hours accumulated rainfall in mm (0300 UTC of 18th October to 0300 UTC of 19th Oct, 2021)
Pantnagar	25 May, 1962	228 (10/07/1990)	403.2
Nainital	31 years of data	313.7 (15/09/1957)	401
Mukteshwar	01 March, 1897	254.5 (18/09/1914)	340.8
Pithoragarh	43 years of data	200.7 (24/06/1921)	212.1

(b)

District	Station	Type of rain gauge	Observed 24 hours accumulated rainfall in mm (0300 UTC of 18th October to 0300 UTC of 19th October, 2021)
Nainital	Nainital	AWS	535
	Jeolikot	AWS	506.5
	Bhimtal	ARG	413
Champawat	Champawat	AWS	593
	Lohaghat	AWS	401
Udham Singh Nagar	Gular Bhoj	ARG	473
	Rudrapur	AWS	484

TABLE 2

Life losses and damages reported by SEOC due to heavy rainfall-induced disasters in Uttarakhand from 17th to 19th October

District	Disaster type	Human losses/damages			Damage to buildings	Damage to roads
		Dead	Injured	Missing		
Nainital	Landslide/heavy rainfall	35	5	-	74	1-National highway 4-State highway 63-Village motorway
Champawat	Landslide/heavy rainfall	11	4	-	2	1-National highway 2-State highway 70-Village motorway
Almora	Landslide/heavy rainfall	6	2	-	40	37-Village motorway
Pithoragarh	Heavy rainfall	3	2	-	-	3-State highway 7-Border roads 40-Village motorway
US Nagar	Heavy rainfall	2	3	-	101	1-Village motorway
Pauri	Landslide/heavy rainfall	3	2	-	-	10-Village motorway
Uttarkashi	Cold/stranding due to snowfall during trekking expedition	10	2	2	-	
Chamoli	Landslide/heavy rainfall	3	4	-	15	80-Village motorway
Bageshwar	Heavy rainfall and Cold/stranding due to snowfall during trekking expedition	6	-	1	-	9-Village motorway

TABLE 3

Chief amount of 24-hour rainfall observed in Uttarakhand. (a) > 115.5 mm rainfall observed at 0300 UTC of 18th October (b) > 150 mm rainfall observed at 0300 UTC of 19th October and (c) > 115.5 mm rainfall observed at 0300 UTC of 20th October, 2021

(a)

District	0300 UTC of 17th to 0300 UTC of 18th October		
	Station	Type of raingauge	Rainfall in mm
Champawat	Champawat	AWS	286
	Pancheshwar	AWS	258
	Bastia	ARG	244
	Lohaghat	AWS	194
	Chalthi	AWS	190
	Champawat	AWS	177.5
	Tanakpur	AWS	172
	Champawat	Manual	160
	Banbasa	Manual	143
	Lohaghat	Manual	133.3
Nainital	Bhimtal	ARG	179
	Nainital	AWS	134
Udham Singh Nagar	Kashipur	AWS	181

(b)

District	0300 UTC of 18th to 0300 UTC of 19th October			District	0300 UTC of 18th to 0300 UTC of 19th October		
	Station	Type of raingauge	Rainfall in mm		Station	Type of raingauge	Rainfall in mm
Almora	Takula	AWS	283	Nainital	Nainital	AWS	535
	Matela	AWS	237.5		Jeolikot	AWS	506.5
	Jageshwar	AWS	230		Bhimtal	ARG	413
	Almora	Manual	220		Nainital	Manual	401
	BhainsiyaChhana	AWS	220		Mukteshwar	Manual	340.8
	Almora	AWS	202		Haldwani	Manual	325.4
	Sult	AWS	190		Mukteshwar	AWS	315.5
	Dwarhat	Manual	184		Betalghat	Manual	268.2
	Bhikiyasain	AWS	170		Haldwani	AWS	242
	Ranikhet	Manual	165		Ramnagar	AWS	227
	Chaukhutia	Manual	158	Pauri	Lansdown	AWS	238
Bageshwar	Shama	AWS	308		Satpuli	AWS	218
	Liti	ARG	299		Rikhnikhal	AWS	185
	Dangoli	ARG	283	Pithoragarh	GanaiGangoli	ARG	325
	Bageshwar	AWS	217		Pithoragarh_Kvk	AWS	242.5
	Kosani	AWS	207		Thal	ARG	242
	Garud	AWS	206		Berinag	ARG	231
	Sama	Manual	205		Pithoragarh	Manual	212.2
	Loharkhet	Manual	204		Dharchula	Manual	196

	Song	AWS	186
	Kapkote	AWS	183.5
	Kanda	AWS	176
	Bageshwar	Manual	157.5
	Kapkot	Manual	157
Chamoli	Karnaprayag	AWS	391
	Auli	AWS	186
	Joshimath	Manual	185.6
	Pandukeshwar	AWS	182
	Tapovan	AWS	158
	Dewal	AWS	157
Champawat	Champawat	AWS	593
	Lohaghat	AWS	401
	Champawat_2	AWS	345
	Devidhura	AWS	338
	Lohaghat	Manual	321.5
	Chalthi	AWS	310
	Lohaghat	ARG	284.9
	Pati	AWS	280
	Bastia	ARG	277
	Champawat	Manual	194

	Pithoragarh	AWS	167
	Didihat	AWS	155
Rudraprayag	Kedarnath	AWS	154
Udham Singh Nagar	GularBhoj	ARG	473
	Pantnagar	Manual	403.2
	Gadarpur	ARG	272
	Khatima	AWS	233
	Kashipur	AWS	166
	Kashipur	Manual	166
	Bajpur	AWS	164
	Rudrapur	AWS	484
	Pantnagar	AWS	375.5

(c)

District	0300 UTC of 19th to 0300 UTC of 20th October		
	Station	Type of raingauge	Rainfall in mm
Champawat	Pancheshwar	AWS	268
	Champawat	AWS	213
	Lohaghat	AWS	178
	Champawat	Manual	153
	Champawat	AWS	138.5
	Chalthi	AWS	126
	Lohaghat	Manual	121.9
	Pati	AWS	121
	Devidhura	AWS	115
Pithoragarh	GanaiGangoli	ARG	130
	Pithoragarh_KVK	AWS	120.5

1875-2010 [Nandargi, S. & Dhar, 2012] showed that one out of five most-severe rainstorms occurred in October and the remaining four occurred in the second fortnight of September over the North-western Himalayan region.

Geographically, culturally and administratively Uttarakhand is divided into two divisions, the western 7 districts come under the Garhwal division and the eastern 6 districts come under the Kumaun division. In the

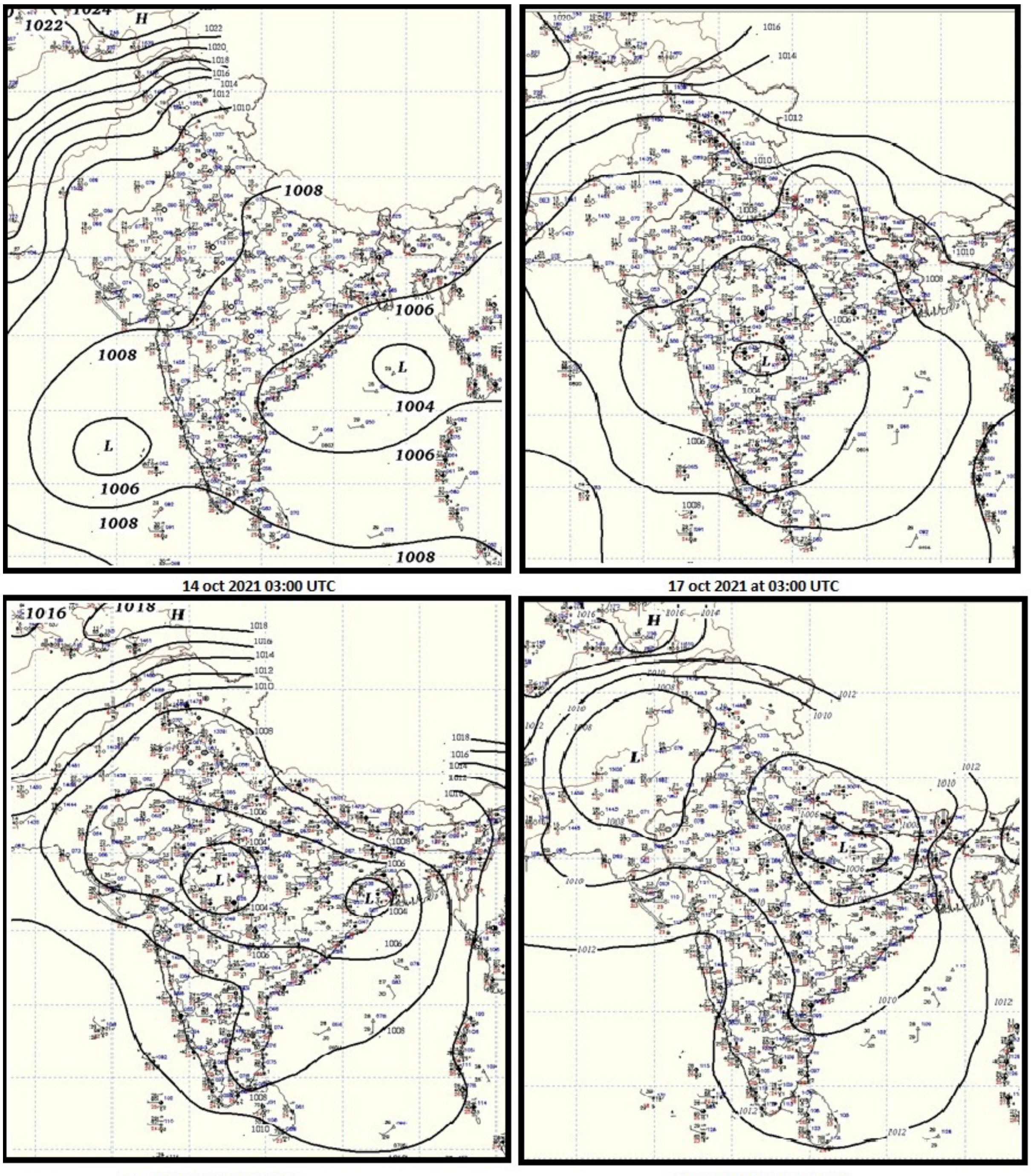
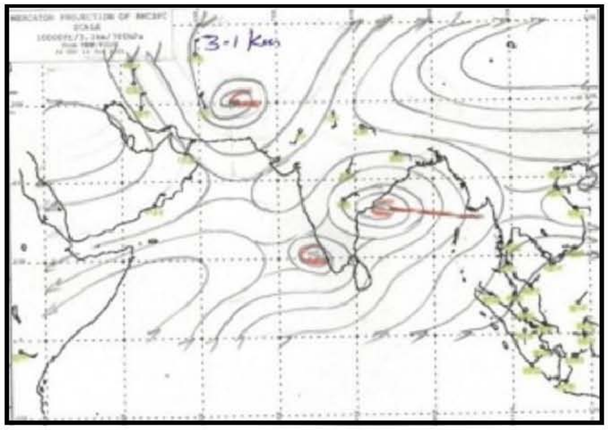
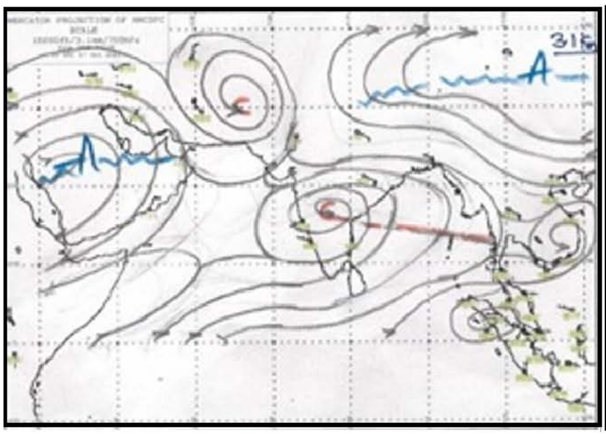


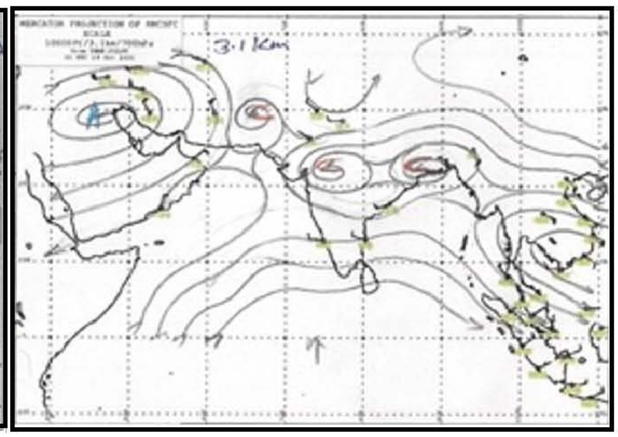
Fig. 2. Analysed surface chart based on 0300 UTC synoptic observations of 14th, 17th, 18th and 19th October, 2021

morning of 19th October, four stations in Uttarakhand recorded the highest ever 24-hour accumulated rainfall [ADGM(R), 2014] since the record-keeping was started by India Meteorological Department (IMD) [Table 1(a)]. The Pantnagar is a class IIb, Mukteshwar is a class I observatory and Nainital & Pithoragarh are part-time observatories run & maintained by IMD. Unlike the June 2013 extremely heavy rainfall event over Uttarakhand which caused extremely heavy rainfall over the whole Uttarakhand state, this event was concentrated over the Kumaun region and adjoining districts of the Garhwal region. Table 1(b) shows the significant 24-hours accumulated rainfall greater than 400 mm recorded in some other stations over Uttarakhand. The catastrophe



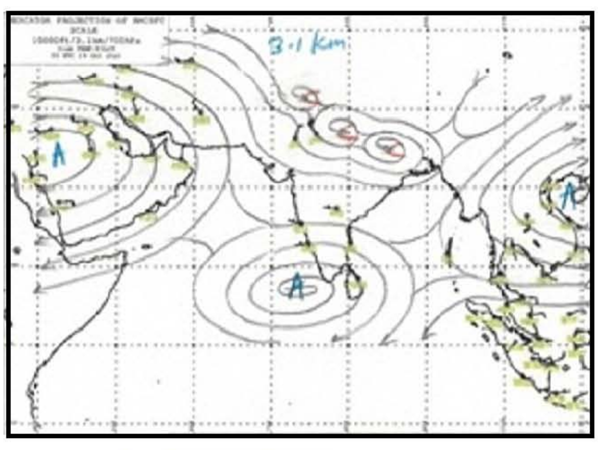
16 oct 2021 at 00:00 UTC

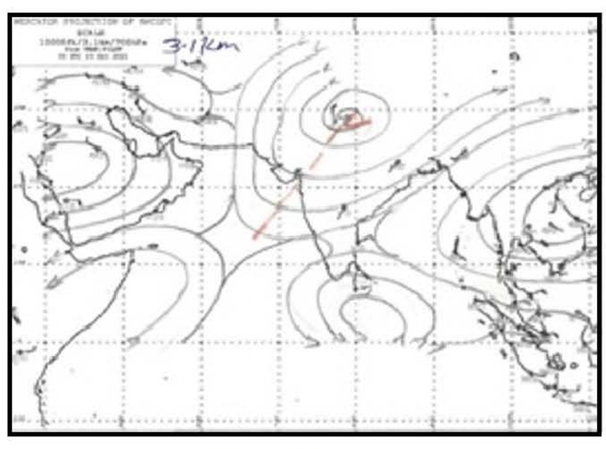




17 oct 2021 at 00:00 UTC

18 oct 2021 at 00:00 UTC





19 oct 2021 at 00:00 UTC

20 oct 2021 at 00:00 UTC

Fig. 3. Analysed 3.1 km level upper air charts based on 0000 UTC observation of 15th to 20th October, 2021

caused by the heavy rainfall in the form of flash floods, landslides and associated debris flow caused major devastation leading to a high death toll over the Kumaun region. The life loss and damages due to landslide, flash flood, inundation, cold/stranding due to snowfall etc. as reported by the Uttarakhand State Emergency Operation

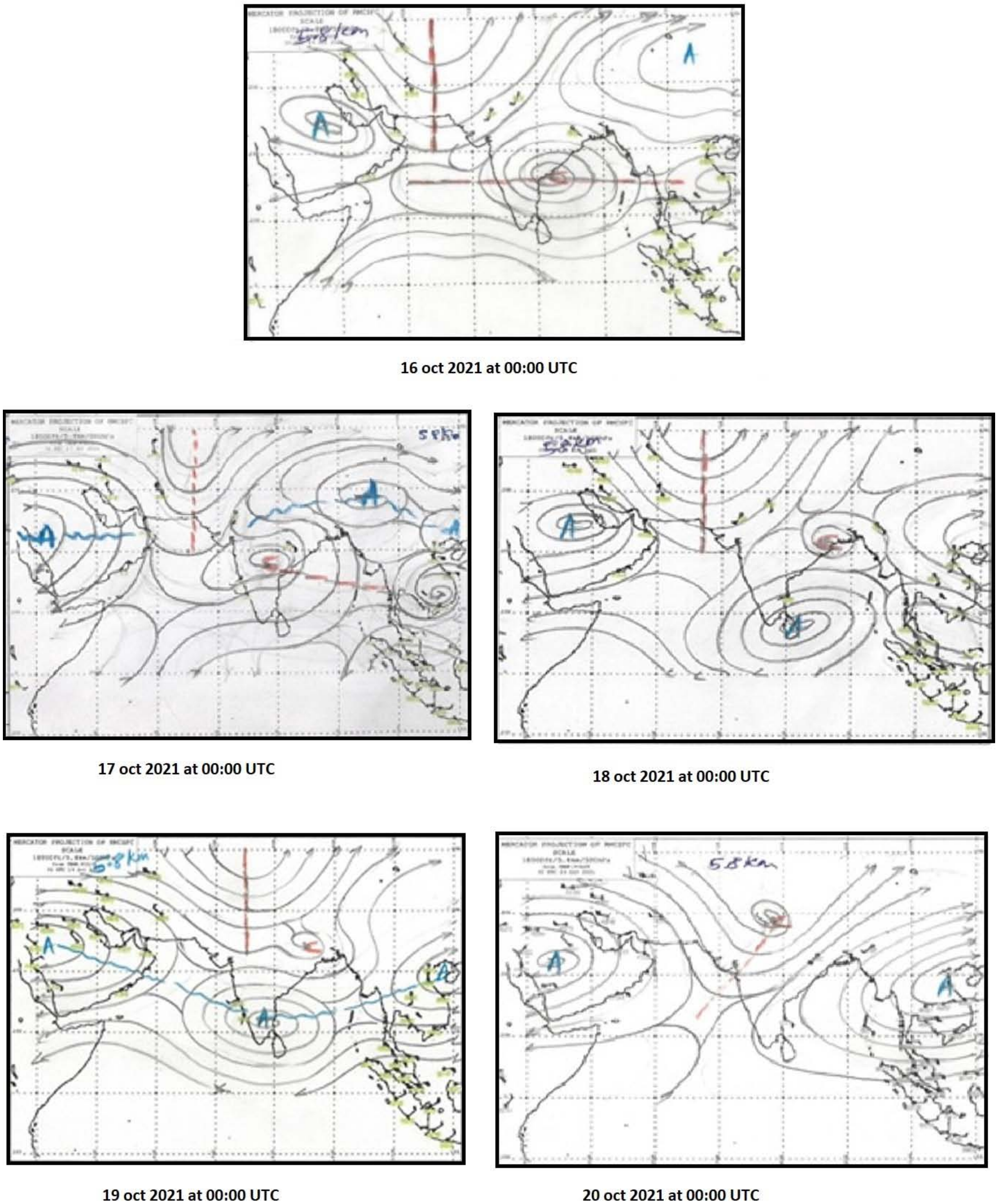


Fig. 4. Analysed 5.8 km level upper air charts based on 0000 UTC observation of 15th to 20th October, 2021

Centre (SEOC) are listed in Table 2. Due to this disaster, 79 people lost their life, 24 were injured and 3 are missing, in addition to that partial to complete damage to 232 buildings, 2 National highways, 9 state highways, 7 border roads and 310 village motorways occurred due to the heavy rainfall. Table 3 shows the chief amount of 24-

hour accumulated rainfall in Uttarakhand. The rainfalls in the table are shown for districts that received very heavy or more rainfall on any of the days from 17th to 19th October.

In recent decades the rainfall in such large quantity over Uttarakhand was reported during 16th-17th June, 2013. Many studies considered it as one of the worst disasters in India [Das, 2013; Sati, 2013; Mishra, 2015]. Due to this, the state incurred a loss of 4,190 (dead and missing) human lives; 11091 big and small animals' lives; and partial to full damage to 19,780 pucca, kuchha houses & huts [Satendra *et al*., 2014]. The synoptic and dynamical features of extreme rainfall event over Uttarakhand during 16-17 June, 2013 were studied by many scholars. These studies [Singh & Chand, 2015; Sikka *et al*., 2015; Chevuturi and Dimri, 2016] show that the interaction between the deep mid-tropospheric trough of western disturbance and strong southeasterly winds to the north of monsoon trough resulted in extreme rainfall. In the present event the single day rainfall is highest ever and the damages in terms of loss of human lives and other losses are significantly lower due to the timely and accurate forecast and the appropriate actions thereof taken by the state government authorities such as halting the movement of tourists & pilgrims, closure of educational institutions and quick response of rescue operations. Another reason for the lesser damage in the areas of exceptionally heavy rainfall is the geology of the affected region. In the current study, the synoptic and dynamic situations, as well as the characteristics of the extreme precipitation and its forecast are analysed in detail.

2. Data and methodology

The all India 0000 UTC upper-air observations, 0300 UTC surface observation from IMD stations and IMD's GFS (T-1534) & WRF Numerical Weather Prediction (NWP) models 0000 UTC analysed wind products are used for the synoptic analysis. The 240 hours forecast products from the global model, *i.e*., IMD-GFS (T-1534) and 72 hours forecast products from the 03 km resolution regional model, *i.e*., IMD-WRF are used to determine the skills in the forecasting of extreme rainfall over Uttarakhand.

Visible, TIR1-10.8 µm channel images, cloud top brightness temperature and satellite-derived upper-level divergence & lower-level convergence from INSAT 3D satellite are analysed for the position, movement and characteristics of the system. In addition, the mid & upper tropospheric water vapour derived winds arealso used for the determination of the real-time position and movement of the western disturbance.

In September 2020 an X-band Doppler weather radar (DWR) was installed at Mukteshwar in the Nainital district. This X-band DWR has an effective radial range of 100 km, therefore, it covers almost all the Kumaun region except the higher reaches of Pithoragarh district. In the Garhwal region the DWR covers many parts of Pauri and Chamoli Districts. The PPI, Maxdisplay (Z), SRI, SRI (ACC) products generated at every 10 minutes interval by the DWR are utilized for the study. The output images of the X-band DWR are processed using JAVA language programme to generate the superimposed images and the spatial frequency distribution of the reflectivity from the volume scans.

Fifteen-minute interval rainfall data from 97 Automatic Weather Station (AWS) and 26 Automatic raingauge Station (ARG) were analysed for determination of the spatial & temporal distribution and intensity of rainfall. The 24-hour accumulated rainfalls from 70 daily rainfall measuring stations of Uttarakhand are also used for this study.

3. Results and discussion

The post-monsoon season is the driest season for Uttarakhand state. The state receives 4% (60.5mm) of the total annual rainfall in three months of the post-monsoon season (October, November & December). However, the Coefficient of Variation (CV) of rainfall is highest during this season as compared to other seasons and CV ranges from 78% to 280%. The rainfall variability is the highest in the small parts of Udham Singh Nagar Champawat and Nainital districts with values of CV ranging between 250% and 280% [ADGM(R), 2014]. The synoptic and dynamic features associated with the 17th to 19th October extreme rainfall event and the methodology for forecasting such exceptionally heavy rainfall are presented in this section.

3.1. *Synoptic analysis*

The following synoptic-scale weather systems and their interaction with one another were observed during the period of the exceptionally heavy rainfall over Uttarakhand.

The Western Disturbance (WD) on 16th October 2021 at 0000 UTC was seen as a cyclonic circulation between 1.5 & 3.1 km above mean sea level (MSL) over southern parts of Afghanistan & neighbourhood with a trough aloft in mid-tropospheric westerlies with its axis at 5.8 km above MSL roughly along Long. 64°E to the north of Lat. 20°N. The WD moved slowly eastwards and laid as a cyclonic circulation over east Afghanistan & neighbourhood at 3.1 km above MSL with a trough aloft

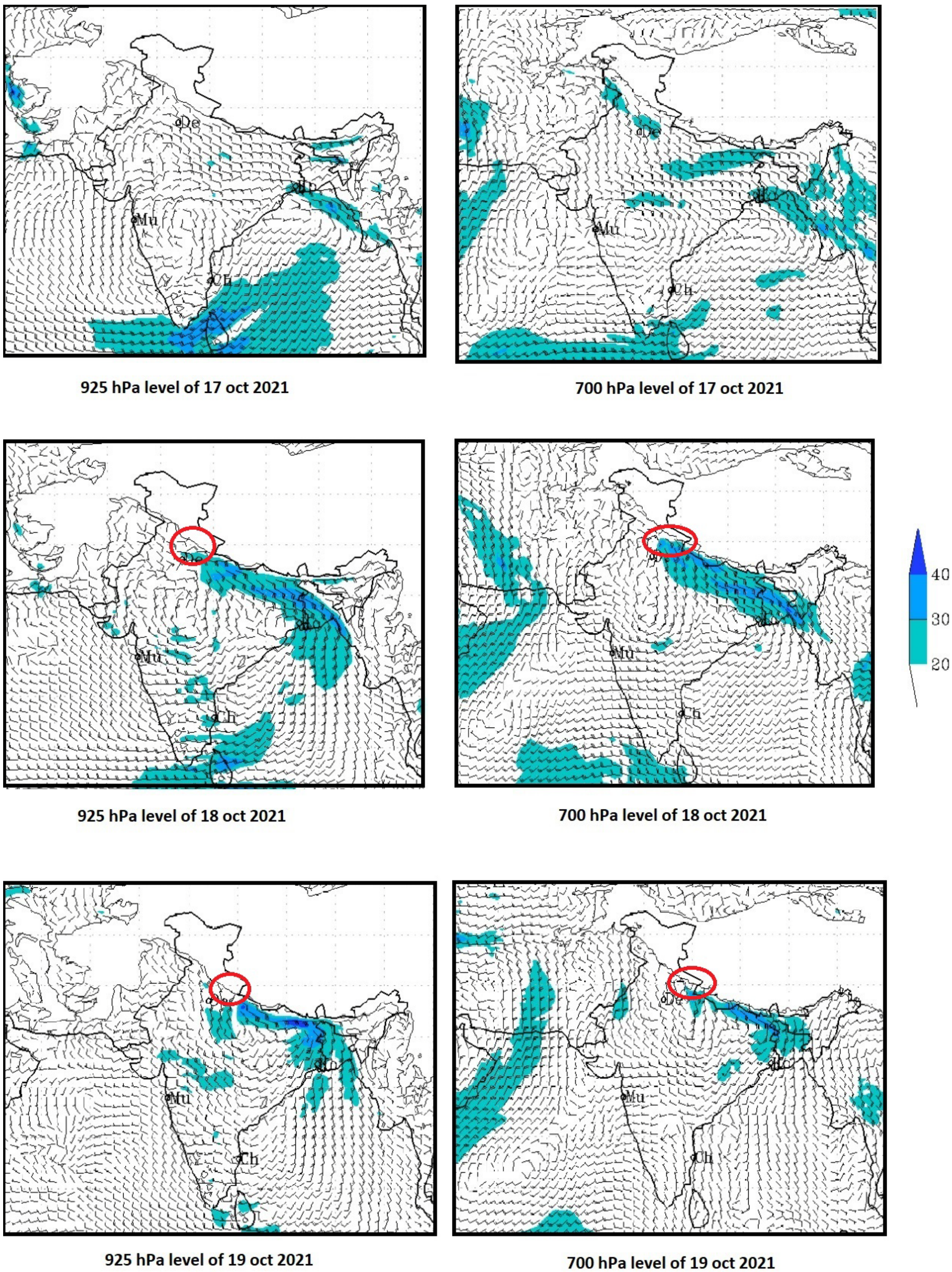


Fig. 5. GFS (T-1534) model based analysed 925 hPa and 700 hPa winds of 17th to 19th October, 2021. Wind speed is in Knots

in mid & upper tropospheric westerlies with its axis at 5.8 km MSL roughly along Long. 67°E to the north of Lat. 20°N on 18th October at 0000 UTC. Thereafter, the WD moved rapidly east north-eastwards and laid as a cyclonic circulation over Punjab & neighbourhood extending upto 3.1 km above MSL with the trough aloft in mid & upper tropospheric westerlies with its axis at 5.8 km above MSL roughly along Long. 75°E to the north of Lat. 23°N on 19th October at 0000 UTC and as a cyclonic circulation over northwest Uttar Pradesh & neighbourhood between 3.1 & 5.8 km above MSL on 20th October. Fig. 3 and Fig. 4 show the position and movement of WD and the trough in mid & upper tropospheric westerlies.

A Low-Pressure Area (LPA) formed over the east-central Bay of Bengal (BoB) & neighbourhood with the associated cyclonic circulation extending upto mid-tropospheric level tilting south-westwards with height in the morning of 14th October, 2021. The LPA moved west-north-westwards and lay centered over north Coastal Andhra Pradesh & adjoining West central Bay of Bengal and the associated cyclonic circulation extends upto 5.8 km above mean sea level tilting southwestwards with height on 16th October and over north Telangana & neighbourhood with the associated cyclonic circulation extending upto 5.8 km above MSL on 17th October. The LPA then moved north-north-westwards and at 0300 UTC of 18th October, it laid over southwest Madhya Pradesh & Neighbourhood with the associated cyclonic circulation extending upto 4.5 km above MSL. In the morning of 19th October, the LPA became less marked, however, the cyclonic circulation laid over central parts of Uttar Pradesh extending upto 4.5 km above MSL. The cyclonic circulation remained stationary over the central parts of Uttar Pradesh till the night of 19th October and became less marked in the morning of 20th October. Fig. 2 shows the movement of LPA on 0300 UTC analysed surface charts.

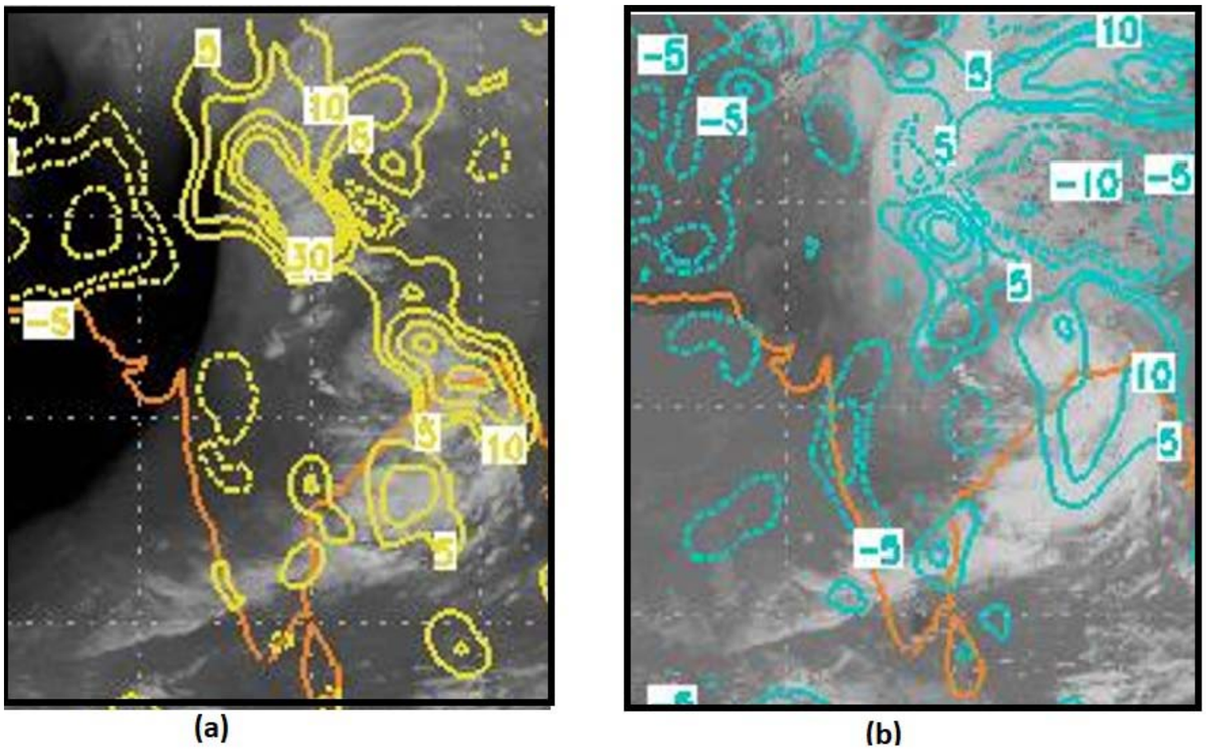
The monsoon depressions and lows recurve north or even northeastwards towards the western Himalayas under the influence of westerly trough [Rao *et al*., 1970]. The large scale environmental wind field surrounding the LPA governs the movement of it. After coming to the close proximity of the westerly trough, the above LPA recurved northwards on 18th October and thereafter, north-eastwards on 19th October.

Under the influence of cyclonic circulation over Gangetic West Bengal & neighbourhood, a Low-Pressure Area formed over West Bengal & adjoining north Odisha with associated cyclonic circulation extending upto 5.8 km above MSL on 18th October. The LPA moved north-westwards and lay centred over south Bihar and adjoining Jharkhand & East Uttar Pradesh with associated cyclonic circulation extending upto 5.8 km above MSL in the morning of 19th October and over Bihar & neighbourhood till the night of 19th October. On 20th October, the LPA became less marked, however, the associated cyclonic circulation over Bihar & neighbourhood persisted and extended upto 1.5 km above MSL. Fig. 2 shows the formation of LPA and its movement on 0300 UTC analysed surface charts.

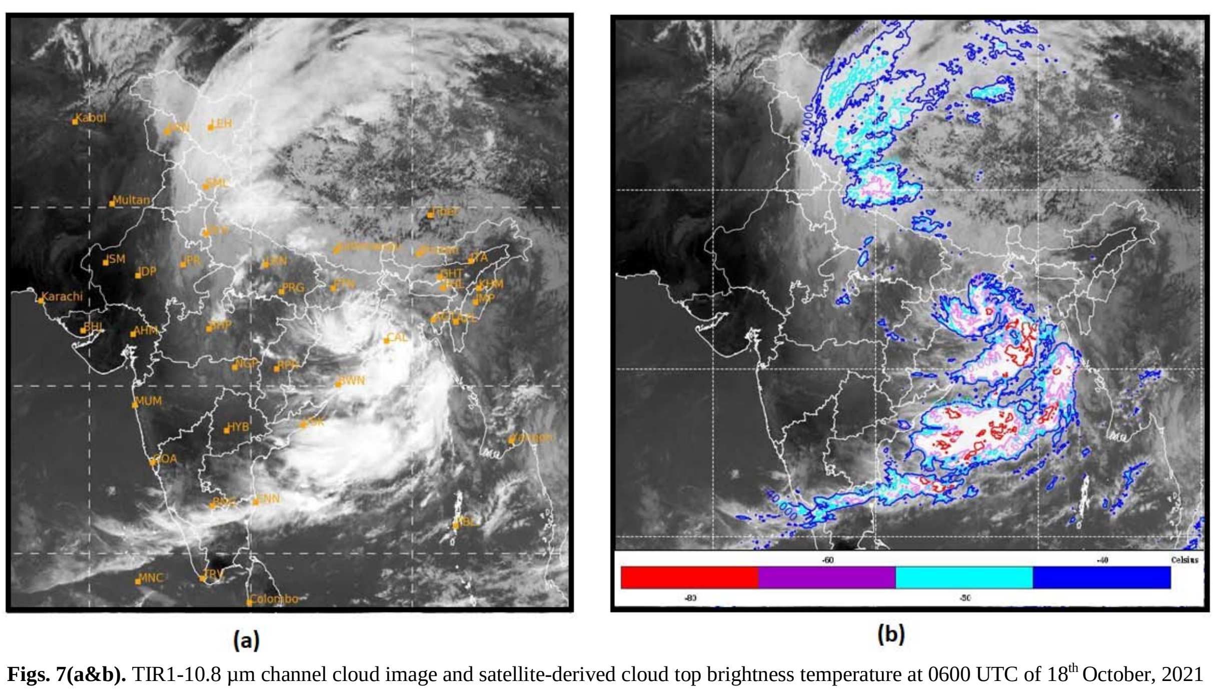
Many studies [Lavers *et al*., 2011; Rao *et al*., 2016] showed the enhanced rainfall in the region of orographic proximity due to the Atmospheric River, a narrow ribbon of high wind speed≥(24 Knots) at lower -levels along which large flux of moisture is transported. They are usually found in the mid-latitude region swinging up & down and their persistence over a region may result in a large amount of water vapour transport.

Due to the above LPAs and their associated upper air cyclonic circulations, the strong southeasterly winds at lower to mid-tropospheric levels, originating from the Bay of Bengal, started intruding into the Indo-Gangetic planes from 17th October. The southeasterly winds strengthen further from the morning of 18th October with a wind speed of 30-40 knots at 925 hPa level. These winds at lower to mid-tropospheric levels were observed till Uttarakhand resulting in strong wind speed convergence over the Uttarakhand state. This region of strong wind convergence shifted eastwards to over foothills of Nepal and adjoining Kumaun region of Uttarakhand on 19th October. Fig. 5 shows the IMD-GFS (T-1534) NWP model-based 925 and 700 hPa analysed winds of 17th to 19th October, 2021. The red circled area shows the region of wind speed convergence. The strong southeasterly winds (Atmospheric River) coming from BoB from 17th to 19th October provided a large amount of continuous moisture supply over the Kumaun region. The upper level divergence provided by the trough in mid and upper tropospheric westerlies as well as the blocking of Atmospheric River in mid and lower tropospheric levels by the WD and the Himalayas over the Kumaun region of Uttarakhand resulted in exceptionally heavy rainfalls.

Past studies on extreme rainfall over western Himalayan region have revealed similar synoptic and dynamic situations as observed during the current event and 16-17 June, 2013 Uttarakhand extreme rainfall events. Ghosh and Veeraraghavan (1975) studied the meteorological conditions responsible for the 6 to 10 August 1973 severe floods in Jammu & Kashmir (J&K). They found the interaction of the recurving low pressure system over north west India, deep penetration of south-easterlies till J&K with vertical extension up to 600 hPa level and the strong divergence caused by the eastward



Figs. 6(a&b). Satellite derived (a) upper level divergence and (b) lower level convergence of wind (in $\times10^{-5}$ /s) at 0600 UTC of 18th October, 2021



Figs. 7(a&b). TIR1-10.8 µm channel cloud image and satellite-derived cloud top brightness temperature at 0600 UTC of 18th October, 2021

moving westerly trough between 300 to 200 hPa levels resulted in exceptionally heavy rainfall triggering severe flooding over J&K. Yadav *et al*. (2017) studied the 5 to 6 September 2014 exceptionally heavy rainfall event over J&K and concluded that the low-pressure area over extreme northwest India, a deep westerly trough/ circulation in middle & upper troposphere over north Pakistan & neighbourhood and confluence of winds from

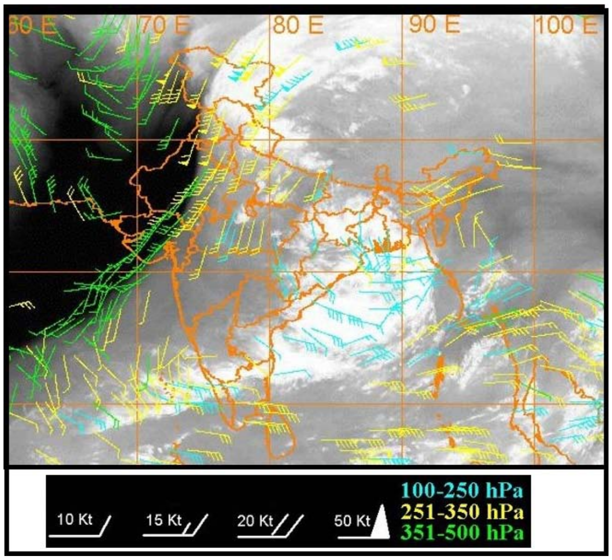


Fig. 8. Satellite derived water vapour wind at 0600 UTC of 18th October, 2021

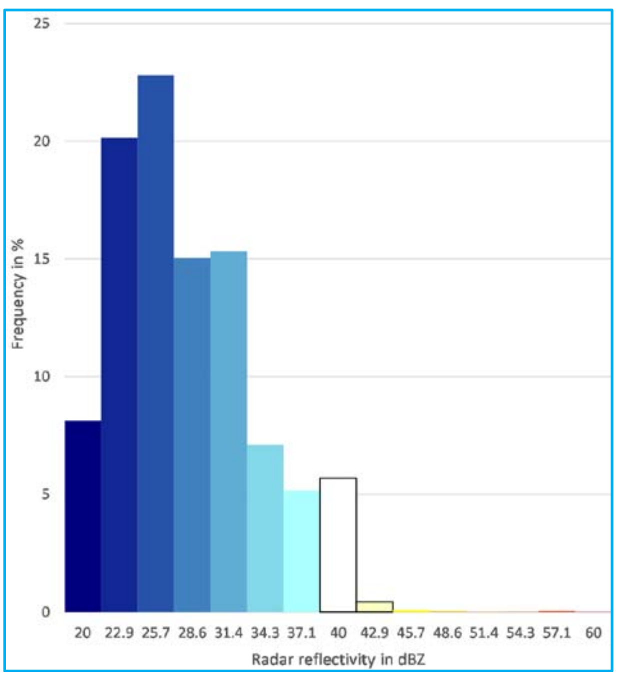


Fig. 9. Three days total frequency distribution of the volume reflectivity of X-band Doppler weather radar

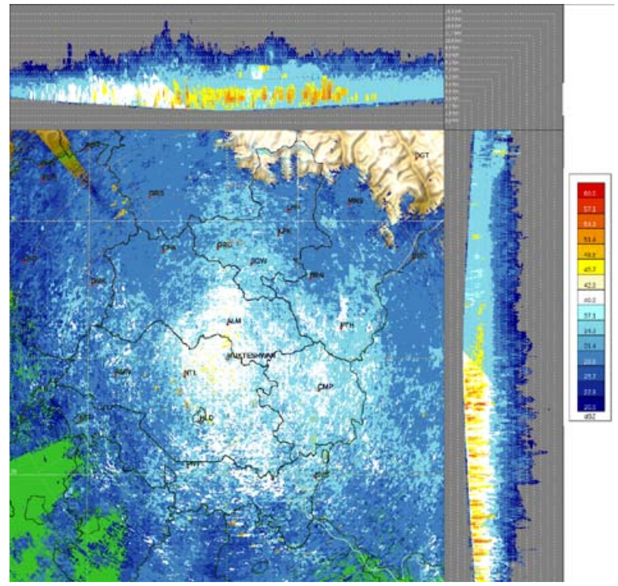
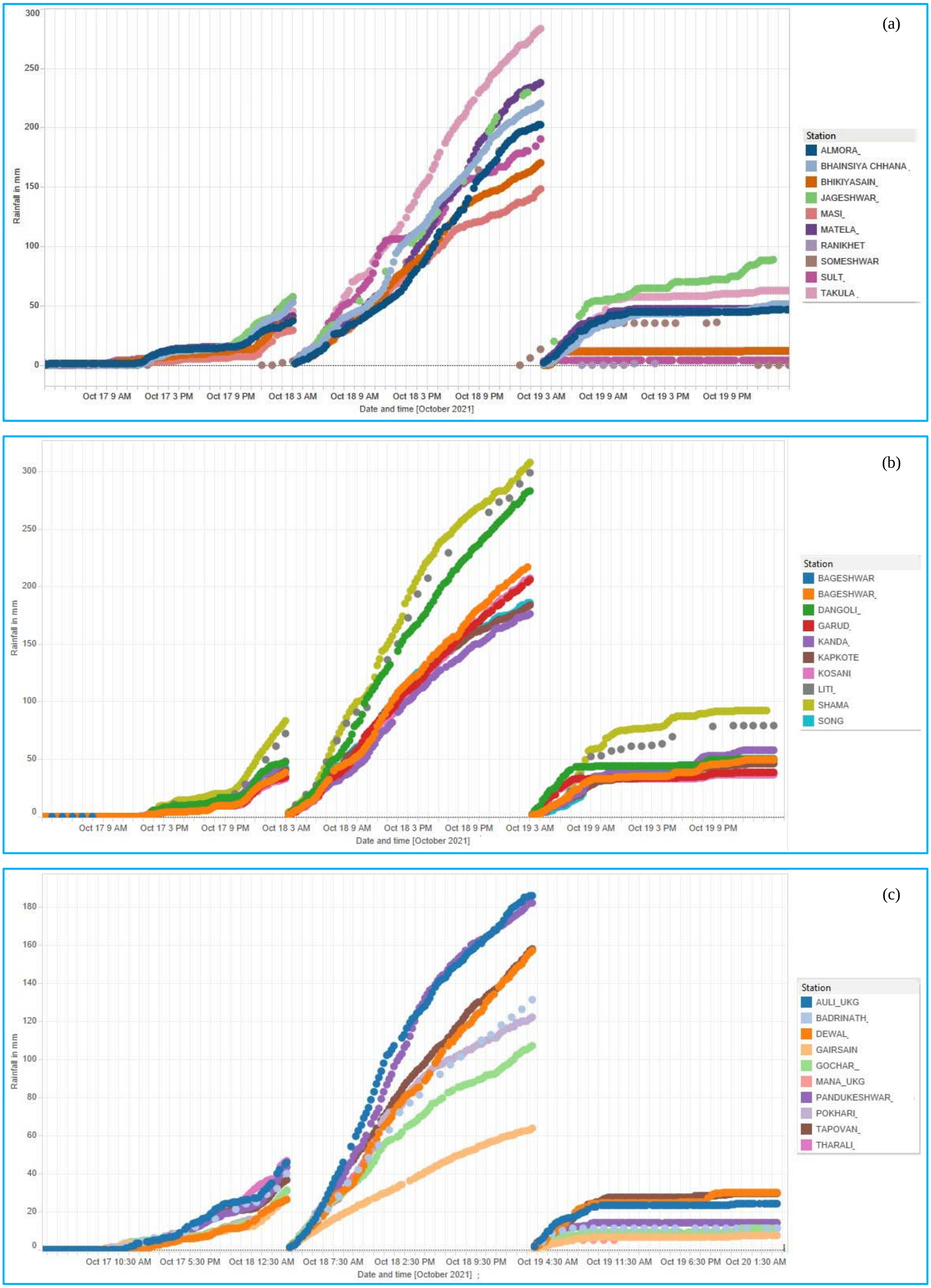


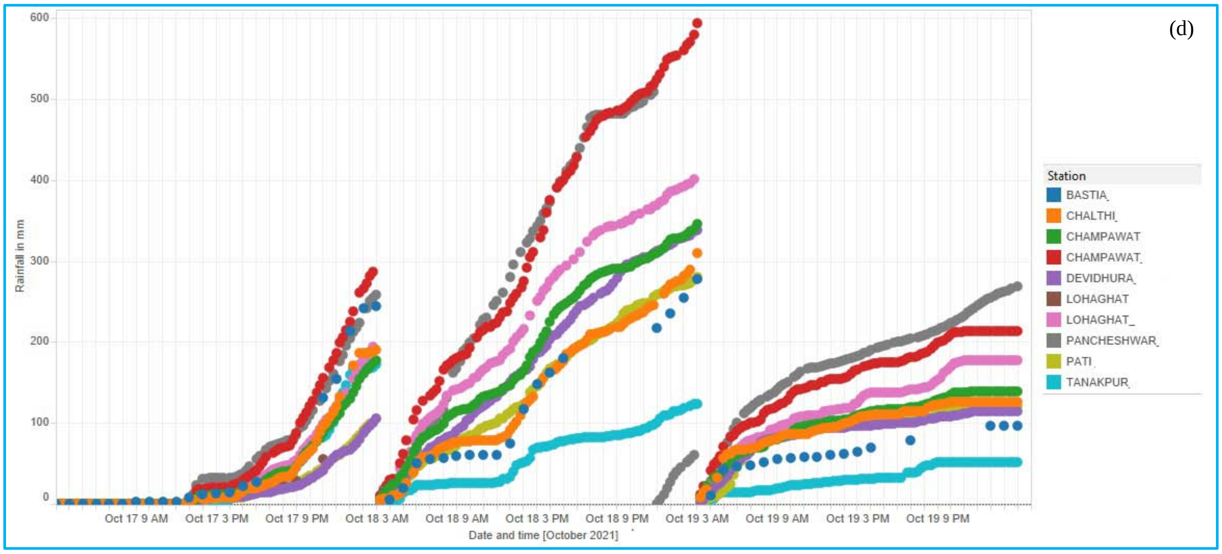
Fig. 10. Three days Superimposed Max-Z image showing highest cloud reflectivity values of Mukteshwar X-band Doppler weather radar

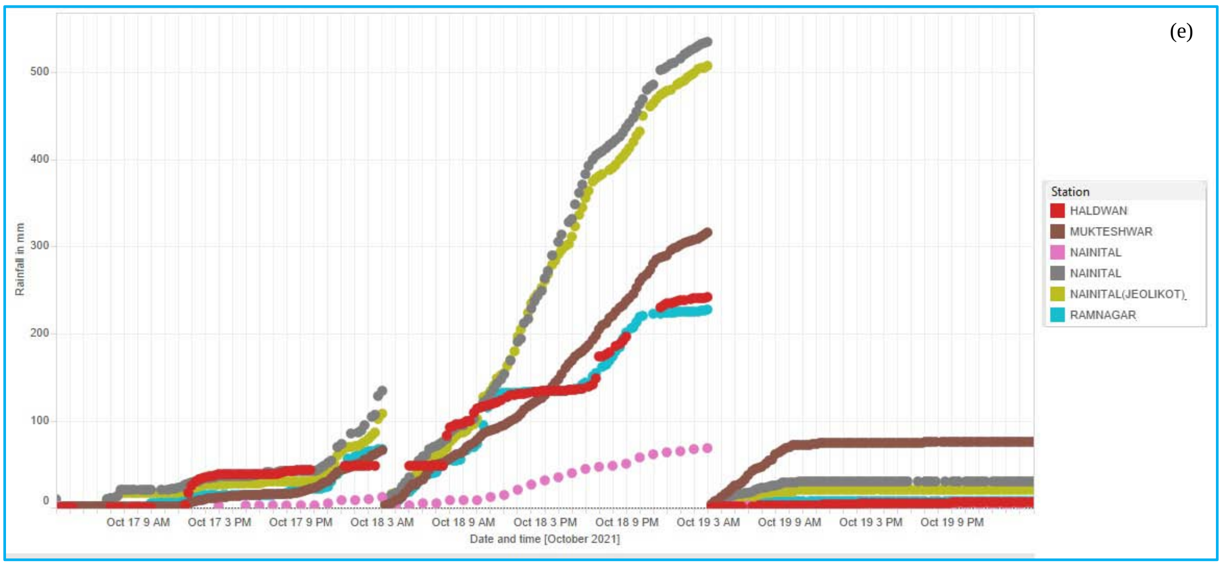
Arabian Sea & Bay of Bengal over Jammu & Kashmir region were favourable for such extreme precipitation. Therefore, these previous studies and the study of current exceptionally heavy rainfall event on 18th October, 2021 over Uttarakhand suggests the interaction of (1) the easterly system (lows or cyclonic circulations) laying over central or northwest India, (2) penetration of strong southeasterly winds from BoB up to the mid-tropospheric levels which can be considered as atmospheric river causing enormous moisture incursion, (3) the mid & upper tropospheric westerly trough and (4) the Orography are favourable for exceptionally heavy rainfall over the zone of interaction in western Himalayan region.

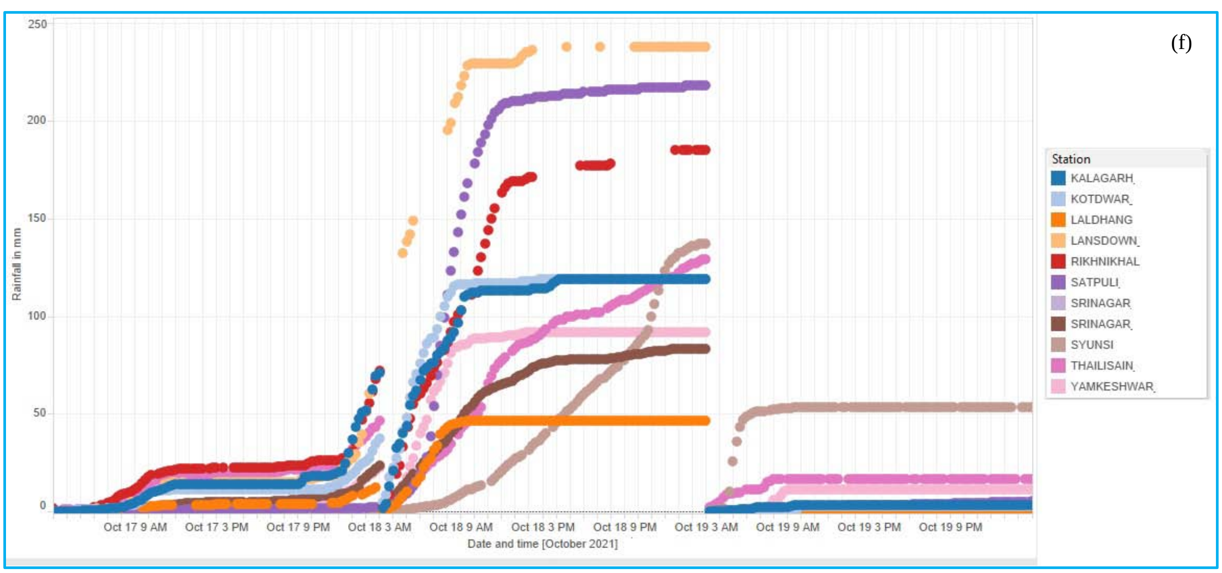
3.2. *Satellite and Radar images*

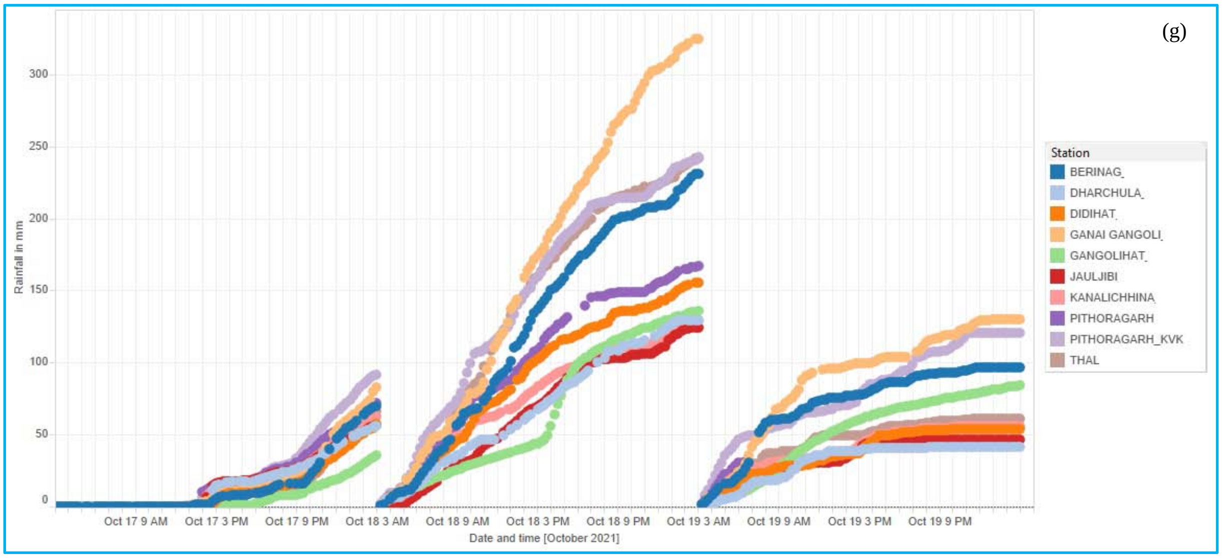
The analysis of satellite images shows that the cloud formation started over Uttarakhand from 2000 UTC of 16th October. However, very light to light rainfall was realised at isolated places mostly over the Garhwal region of Uttarakhand till 0300 UTC of 17th October. The maximum clouding and thus, light to moderate rainfall occurred over the Garhwal region till 0900 UTC of 17th October. Thereafter the thick cloud mass shifted over the Kumaun region and rainfall started there. Figs. 11 & 12 shows the Automatic Weather Station (AWS) based rainfall graph. With the eastward movement of the WD, the region of maximum low-level convergence (LLC) and upper-level divergence (ULD) also shifted eastwards coving the entire Kumaun region. Fig. 6 shows the satellite-derived ULD of the order of 30×10^{-5} per second and LLC of the order of 5×10^{-5} per second at 0600 UTC of 18th October. The thick cloud mass and area of highest cloud top brightness temperature (CTBT) remained over the Kumaun region and its adjoining districts of Garhwal region with a little fluctuation in position and intensity till 19th October. Fig. 7 shows the TIR1-10.8 µm channel image and CTBT image of maximum cloud mass at 0600 UTC of 18th October. The satellite-derived water vapour

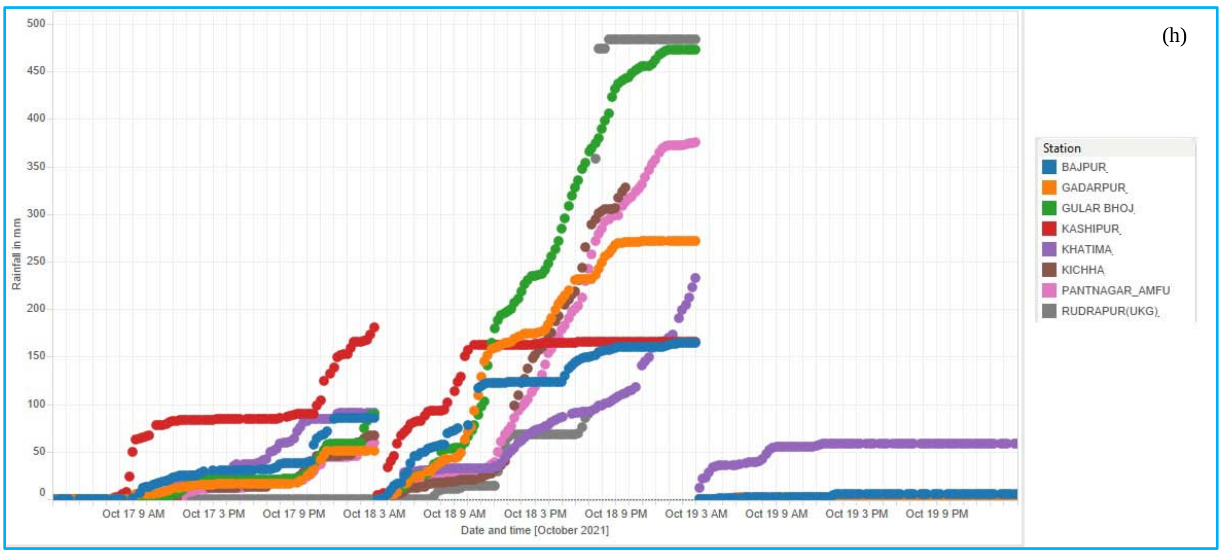

(a)
Rainfall in mm
300
250
200
150
100
50
0
Oct 17 9 AM
Oct 17 3 PM
Oct 17 9 PM
Oct 18 3 AM
Oct 18 9 AM
Oct 18 3 PM
Oct 18 9 PM
Oct 19 3 AM
Oct 19 9 AM
Oct 19 3 PM
Oct 19 9 PM
Date and time [October 2021]
Station
ALMORA_
BHAINSIYA CHHANA_
BHIKIYASAIN_
JAGESHWAR_
MASI_
MATELA_
RANIKHET
SOMESHWAR
SULT_
TAKULA_
(b)
Rainfall in mm
300
250
200
150
100
50
0
Oct 17 9 AM
Oct 17 3 PM
Oct 17 9 PM
Oct 18 3 AM
Oct 18 9 AM
Oct 18 3 PM
Oct 18 9 PM
Oct 19 3 AM
Oct 19 9 AM
Oct 19 3 PM
Oct 19 9 PM
Date and time [October 2021]
Station
BAGESHWAR
BAGESHWAR_
DANGOLI_
GARUD_
KANDA_
KAPKOTE
KOSANI
LITI_
SHAMA
SONG
(c)
Rainfall in mm
180
160
140
120
100
80
60
40
20
0
Oct 17 10:30 AM
Oct 17 5:30 PM
Oct 18 12:30 AM
Oct 18 7:30 AM
Oct 18 2:30 PM
Oct 18 9:30 PM
Oct 19 4:30 AM
Oct 19 11:30 AM
Oct 19 6:30 PM
Oct 20 1:30 AM
Date and time [October 2021]
Station
AULI_UKG
BADRINATH_
DEWAL_
GAIRSAIN
GOCHAR_
MANA_UKG
PANDUKESHWAR_
POKHARI_
TAPOVAN_
THARALI_


(d)
Rainfall in mm
Date and time [October 2021]
Station
BASTIA_
CHALTHI_
CHAMPAWAT
CHAMPAWAT_
DEVIDHURA_
LOHAGHAT
LOHAGHAT_
PANCHESHWAR_
PATI_
TANAKPUR_


(e)
Rainfall in mm
Date and time [October 2021]
Station
HALDWAN
MUKTESHWAR
NAINITAL
NAINITAL
NAINITAL(JEOLIKOT)_
RAMNAGAR


(f)
Rainfall in mm
Date and time [October 2021]
Station
KALAGARH_
KOTDWAR_
LALDHANG
LANSDOWN_
RIKHNIKHAL
SATPULI_
SRINAGAR_
SRINAGAR_
SYUNSI
THAILISAIN_
YAMKESHWAR_





Figs. 11(a-h). The observed daily cumulative rainfall from 0300 UTC of 17th to 0300 UTC of 19th October, 2021 received from the GPRS/3G/4G/satellite-based AWS in (a) Almora (b) Bageshwar (c) Chamoli (d) Champawat (e) Nainital (f) Pauri (g) Pithoragarh (h) Udham Singh Nagar districts

winds (Fig. 8) shows the position of trough in westerlies between 500-250 hPa levels roughly along Long. 68°E to the north of Lat.20°N at 0600 UTC of 18th October.

Different products like PPI, Max-Z, SRI, SRI (Acc) etc. generated by the X-band DWR installed at Mukteshwar were also analysed for this study. These products are generated at every 10 minutes interval, thus 144 images of each product are generated in 24 hours. The spatial and temporal analysis of thevolume scan generated by the radar from 17th to 19th October were carried out. The spatial reflectivity, *i.e.*, in horizontal & vertical planes from DWR were derived from the Max display (Z) product generated at every 10 minutes interval during these three days by the DWR. The analysis shows that the reflectivity of the clouds were in the range of 20 to 40 dBZ at 99% of the time and 99% of the area during these 3 days. Fig. 9 shows the frequency distribution of the reflectivity values generated by the volume scan from 17th to 19th October. On most occasions, *i.e.*, around 23% occasions the reflectivity was 25.7 ± 2.86 dBZ and on 20% occasions, it was 22.9 ± 2.86 dBZ.

The 432 Max (Z) reflectivity images of 17th to 19th October were merged to analyse the cloud covered area and the nature of clouds and precipitation. The higher

TABLE 4

District-wise average rain rate and station highest rain rate during the event

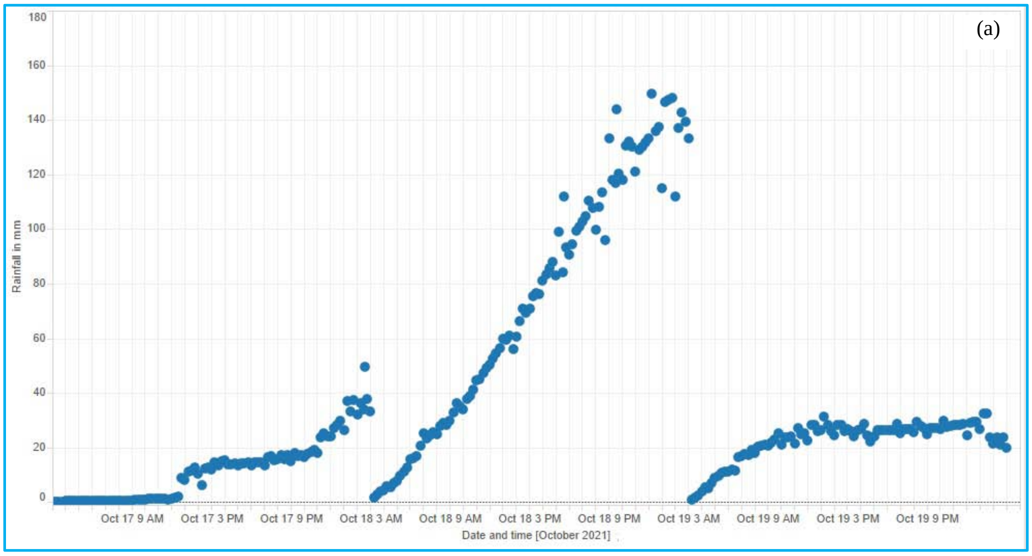
Districts	District average rain rate of highest intensity spell (mm/h)	Station	Highest rain rate (mm/h)	Date	Start time in UTC	End time in UTC
Almora	8	Takula	24	18-Oct	0615	0715
Bageshwar	10	Shama	31	18-Oct	1130	1230
Chamoli	6	Auli	16	18-Oct	1100	1200
Champawat	16	Champawat	53	18-Oct	1530	1630
		Pancheshwar	51	18-Oct	0800	0900
Nainital	15	Jeolikot	44.5	18-Oct	1245	1345
		Nainital	52	18-Oct	1700	1800
Pauri	13	Satpuli	60.5	18-Oct	0645	0745
Pithoragarh	9	Ganaigangoli	28.5	18-Oct	1045	1145
Udham Singh Nagar	19	Pantnagar_amfu	59.5	18-Oct	1830	1930
		Gularbhoj	85	18-Oct	1115	1215
		Kichha	68.5	18-Oct	1245	1345

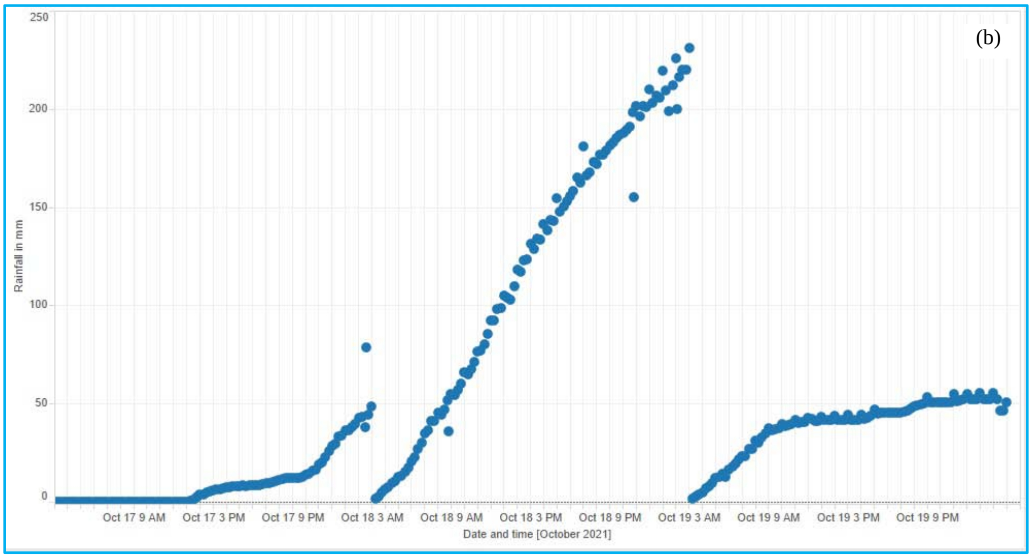
reflectivity values were given higher priority for display, *i.e.*, higher reflectivity values were overlaid over the lower values during super position. Fig. 10 shows the final Max (Z) superimposed image. It can be seen that the maximum patches of the white and yellow/orange colours, *i.e.*, reflectivity more than 40 dBZ are over Nainital, Champawat, Almora, Udham Singh Nagar districts and southern parts of Pithoragarh district. During the period the average height of clouds was 9-10 km with the maximum cloud height reaching up to 13.5 km at a place northwest of Pantnagar station near the district boundary of Nainital and Udham Singh Nagar districts. However, the heights of the high reflectivity clouds (reflectivity≥ 45 dBZ) were less than 6 km and they mostly formed at the southern part of the Kumaun region along the Himalayan foothills. This suggests the role of orography in blocking and lifting the south-easterly moist winds resulting in the shallow convection and formation of thick low-medium clouds.

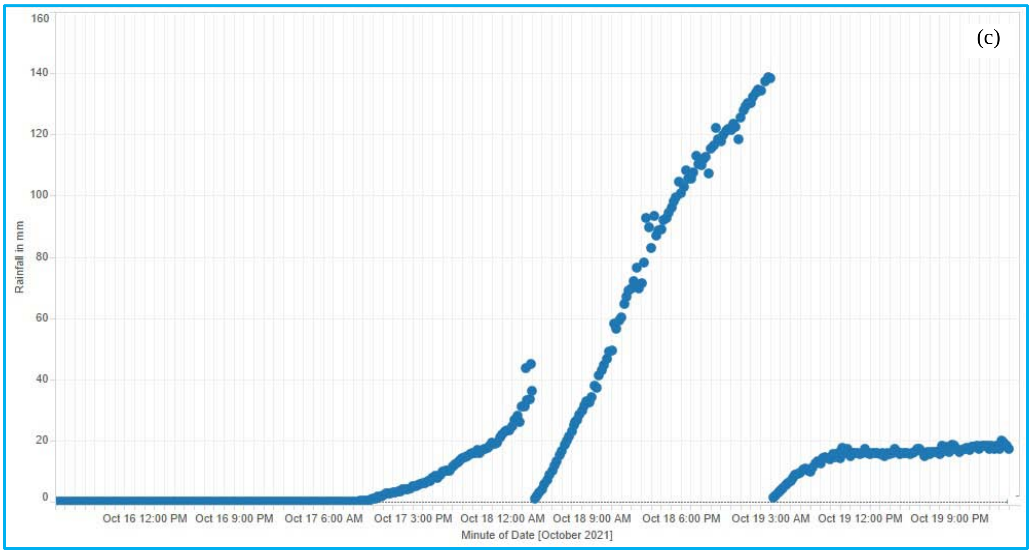
3.3. *Rainfall intensity*

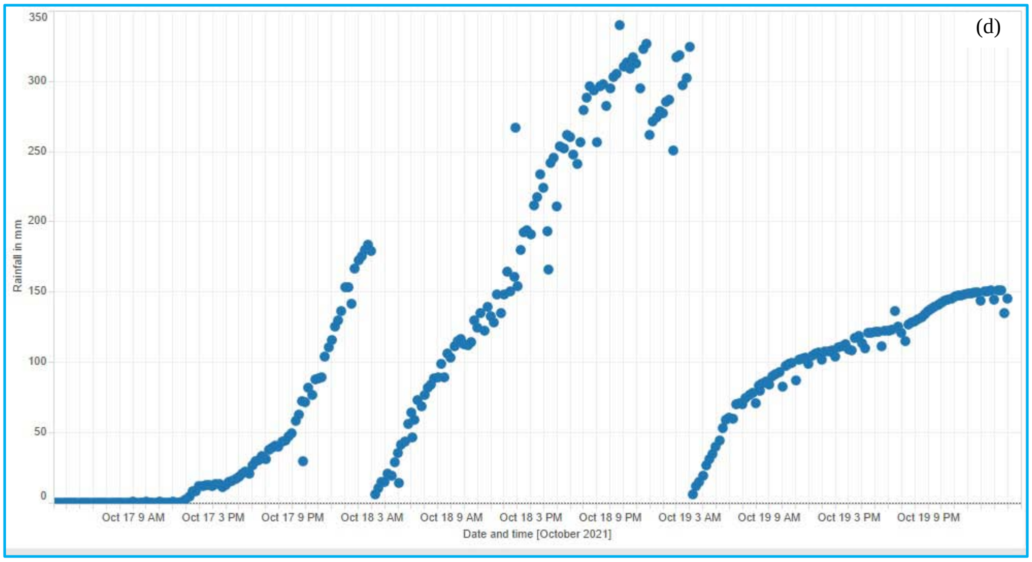
The cloud reflectivity values (Z) generated by DWR is proportional to the rain rate (R) andthis relationship is also known as the Z-R relationship ($Z = aR^b$ where a and b are empirical constants). This Z-R relationship could be linear [Steiner *et al.*, 2004; List, 1988] or nonlinear as the classic Marshall Palmer equation ($Z = 200R^{1.6}$) [Marshall and Palmer, 1948]. During the above event, the cloud reflectivity values were less than 40 dBZ thus representing light to moderate intensity rainfall. India Meteorological Department has classified the intensity of rainfall based on hourly rain rate [ADGM(R), 2015]. The 15-minute interval GPRS/ 3G/4G/satellite based AWS/ARG data from 17th to 19th October were analysed for individual districts. Fig. 11 also shows the 24 hours accumulated rainfall from 17th to 19th October. The 24 hours accumulated rainfall is measured from 0300 UTC of the first day till 0300 UTC of the next day. The rain rate based on 15-minute interval data ofthe districts that experienced very heavy to exceptionally heavy rainfall is plotted in Fig. 11. The AWS rainfall observations show that the rainfall over the Kumaun region started after 0900 UTC of 17th October. Table 4 shows the district average rain rate of the highest intensity rainfall spell and the name of the highest rain rate experiencing stations in each district along with the duration and rain rate of such spell. The district average rain rate of the highest intensity rainfall spell during 3 days were found to be of light to moderate intensity (10-20 mm/hour) with extremely intense spells (50-100 mm/hour) of around 1-hour duration in 7 stations of Udham Singh Nagar, Champawat, Nainital and Pauri districts.

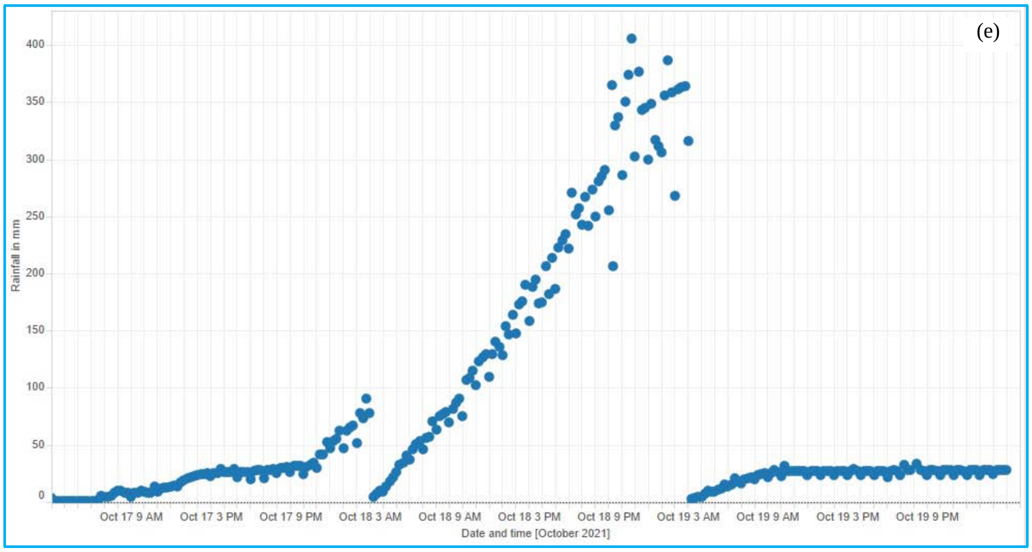
Udham Singh Nagar district experienced the highest average rain rate (19 mm/h) followed by Champawat and Nainital districts. Gular-bhoj ARG station in US Nagar experienced the highest rain rate of 85 mm/hour between 1115 to 1215 UTC on 18th October. Another ARG station Kichha experienced a rain rate of 68.5 mm/hour between 1245 to 1345 UTC on 18th October. The remaining one station in US Nagar, two in Champawat, one in Nainital and one in Pauri district experienced rain-rate between 51 and 60.5 mm/h.

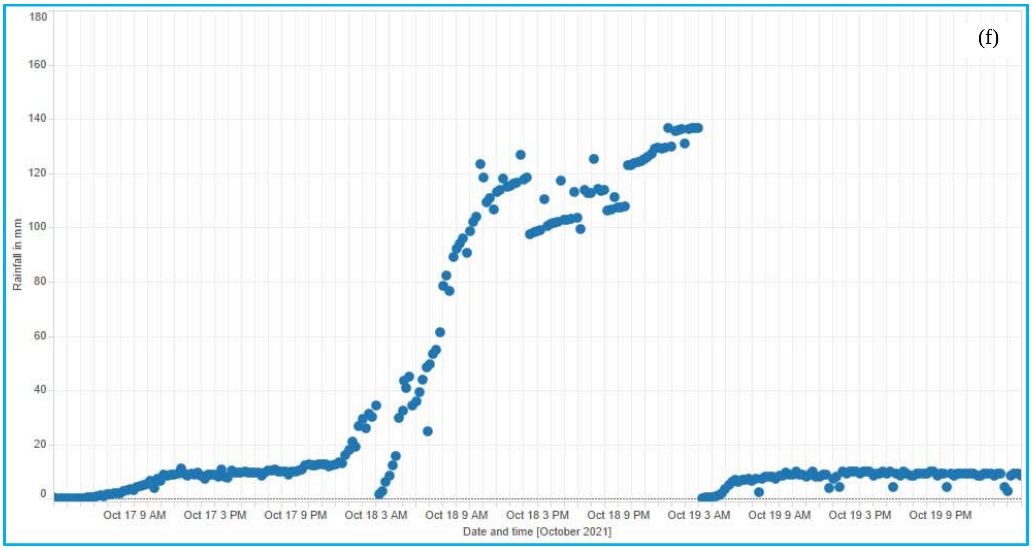

(a)
Rainfall in mm
180
160
140
120
100
80
60
40
20
0
Oct 17 9 AM
Oct 17 3 PM
Oct 17 9 PM
Oct 18 3 AM
Oct 18 9 AM
Oct 18 3 PM
Oct 18 9 PM
Oct 19 3 AM
Oct 19 9 AM
Oct 19 3 PM
Oct 19 9 PM
Date and time [October 2021]

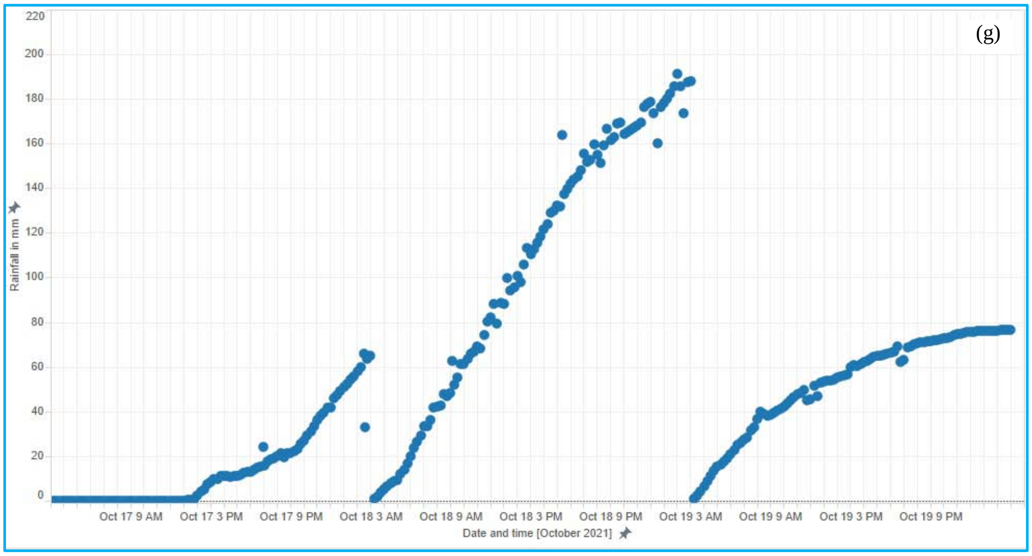

(b)
Rainfall in mm
250
200
150
100
50
0
Oct 17 9 AM
Oct 17 3 PM
Oct 17 9 PM
Oct 18 3 AM
Oct 18 9 AM
Oct 18 3 PM
Oct 18 9 PM
Oct 19 3 AM
Oct 19 9 AM
Oct 19 3 PM
Oct 19 9 PM
Date and time [October 2021]

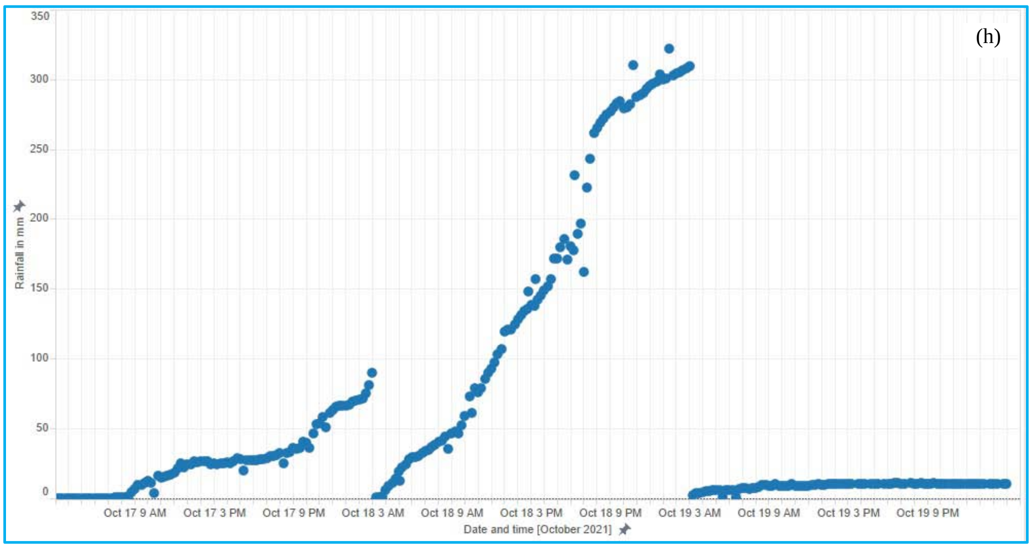

(c)
Rainfall in mm
160
140
120
100
80
60
40
20
0
Oct 16 12:00 PM
Oct 16 9:00 PM
Oct 17 6:00 AM
Oct 17 3:00 PM
Oct 18 12:00 AM
Oct 18 9:00 AM
Oct 18 6:00 PM
Oct 19 3:00 AM
Oct 19 12:00 PM
Oct 19 9:00 PM
Minute of Date [October 2021]


(d)
Rainfall in mm
Date and time [October 2021]


(e)
Rainfall in mm
Date and time [October 2021]


(f)
Rainfall in mm
Date and time [October 2021]





Figs. 12(a-h). The district average rainfall rate from 0300 UTC of 17thto 0300 UTC of 19thOctober, 2021 of (a) Almora (b) Bageshwar (c) Chamoli (d) Champawat (e) Nainital (f) Pauri (g) Pithoragarh (h) Udham Singh Nagar districts

The Gular-bhoj station received the second-highest rain rate as 35 mm/h from 1045 to 2100 UTC of 18 October, Kichha as 40 mm/h from 1300 to 1915 UTC of 18 October, Pantnagar as 31 mm/h from 1215 to 2015 UTC of 18 October, Champawat as 36 mm/h from 1300 to 1930 UTC of 18 October, Pancheshwar as 30 mm/h from 2245 UTC of 17 Oct to 1900 UTC of 18 Oct and Nainital as 41 mm/h from 1230 to 1830 UTC of 18 Oct. These very intense rainfall spells (30-50 mm/h) lasted from 6 to 10 hours and in one case up to 21 hours and resulted in maximum rainfall accumulation over these stations. The district average rain rate for the individual day from 17th to 19th October is plotted in Fig. 12. The rain rate started increasing from 2100 UTC of 17th October till 0600 UTC of 19th October over most districts of Kumaun region and adjoining districts of Garhwal region of Uttarakhand. As per the rain rate based rainfall intensity, the cloud burst (R≥ 100 mm/h) event was not observed at any station in Uttarakhand during this event. The radar generated cloud reflectivity, cloud height and rain rate products also show lesser intensity rainfall for a longer period over Kumaun region of Uttarakhand.

3.4. *Forecast based on NWP models*

The 10th October 0000 UTC based24-hours accumulated rainfall product of GFS model forecasted 40-130 mm rainfall at most places with 130-200 mm rainfall

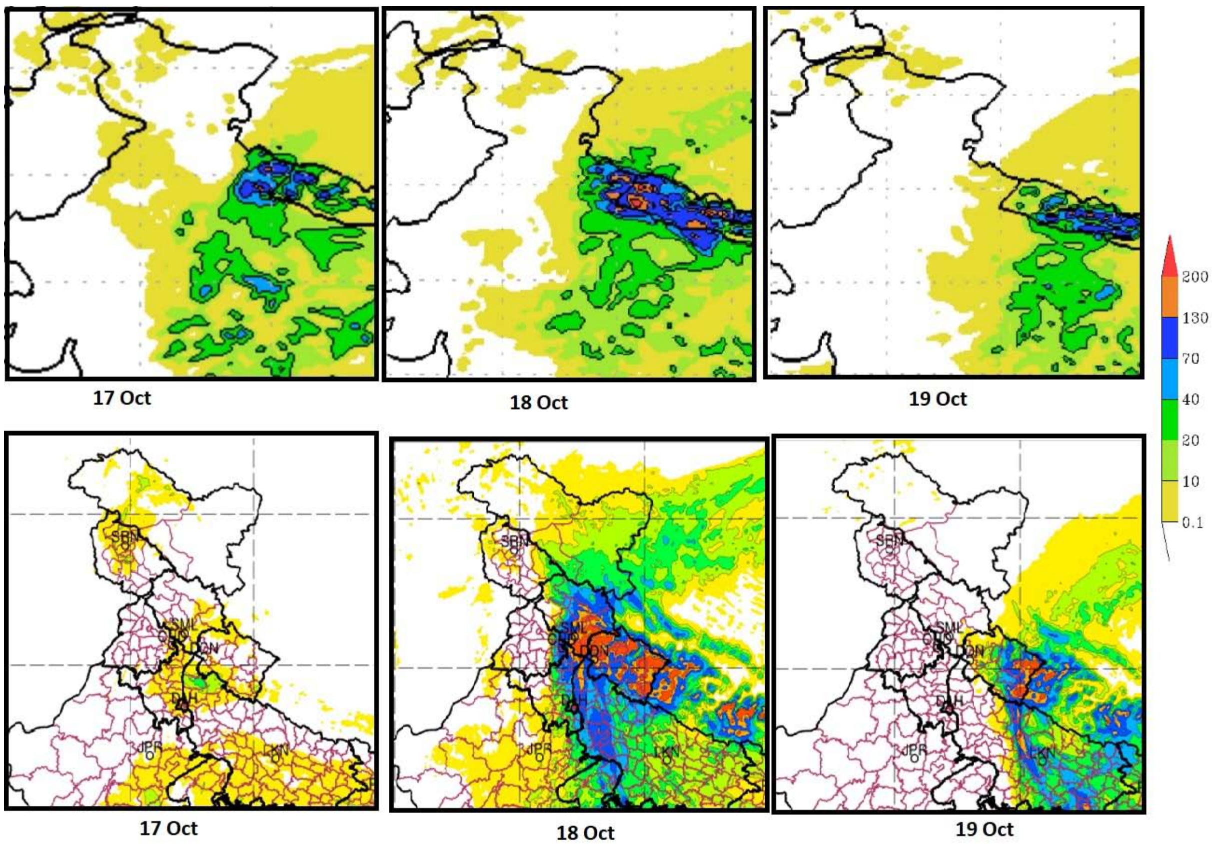


Fig. 13. The 24-hours accumulated rainfall forecast from (upper row) GFS model with the lead time of 5 days and (lower row) WRF model with the lead time of 3 days

at isolated places in Uttarakhand on 18th and 19th October. For 17th October, it forecasted 0.1 to 40 mm rainfall especially over the Kumaun region and 40-130 mm rainfall over the region in Nepal adjacent to Kumaun region. The successive runs of the GFS model from 11th to 13th October reduced the forecasted rainfall amount and distribution however, it maintained the 40-130 mm rainfall forecast over Uttarakhand with minor fluctuation on the date of peak activity. From 14th October onwards the GFS model increased the forecasted rainfall amount and on 15th October it predicted rainfall of more than 200 mm at isolated places in the Kumaun region. The model continuously showed relatively more rainfall over the Kumaun region than the Garhwal region. The 16th October 0000 UTC based 24-hours accumulated rainfall product of WRF model also predicted the 70-130 mm rainfall over most places and more than 200 mm rainfall at a few places over Uttarakhand with equal distribution over Garhwal and Kumaun region on 18th October. The 17th October run of the WRF model slightly reduced the distribution of >200 mm rainfall forecast of 18th October from the Garhwal region. On 18th October the model forecast showed the >200 mm rainfall mostly over Kumaun region and at isolated places over the Garhwal region. Fig. 13 shows the 24-hours accumulated rainfall forecast from the GFS and WRF model with the lead time of 5 days and 3 days respectively. Fig. 1 shows the observed 24-hours accumulated rainfall from 17th to 19th October. Visual comparison of forecasted and observed rainfall maps (Fig. 13 & Fig. 1) shows a very good accuracy, consistency and 5-10 days lead time of NWP model output for this event.

3.5. *Forecasting of extremely heavy rainfall*

Based on the synoptic analysis of surface and upper air charts of 14th October and the NWP model guidance, the district-wise extremely heavy rainfall warning forecast from17th to 19th October was issued by the Meteorological Centre, Dehradun on 14th October. The forecast bulletin was regularly updated thereafter and the red warning was issued on 16th October for forecasted extremely heavy rainfall for18th October. In addition to the regular bulletins, the special press release was also issued on 16th, 17th, 18th & 19th October containing the rainfall forecast, expected impact and advisories for the public for necessary preparations as well as the state government authorities for the planning of effective prevention &

Weather Warning for Uttarakhand:

17.10.2021	• Heavy to very heavy rainfall likely to occur at isolated places in hills of Uttarakhand. • Moderate Thunderstorm accompanied with lightning/ Hail and squall (60-70 KMPH gusting up to 80 KMPH) likely to occur at isolated places in Uttarakhand.
18.10.2021	• Heavy to very heavy rain likely to occur at isolated places in Haridwar and Udham Singh Nagar districts of Uttarakhand. • Heavy to very heavy rainfall likely to occur at many places with extremely heavy rainfall at isolated places in Uttarkashi, Chamoli, Rudraprayag, Pithoragarh, Bageshwar, Almora, Nainital, Champawat, Dehradun, Tehri and Pauri districts of Uttarakhand. • Moderate to severe thunderstorm accompanied with lightning/ Hail and squall (60-70 KMPH gusting up to 80 KMPH) likely to occur at a few places in Uttarakhand.
19.10.2021	• Heavy rain likely to occur at isolated places in Pithoragarh, Bageshwar and Chamoli districts of Uttarakhand. • Thunderstorm accompanied with lightning/ Hail likely to occur at isolated places in hills of Kumau region of Uttarakhand.

District-level impact and advisory for severe weather:

DATE	WEATHER WARNING	IMPACT	SUGGESTED ACTIONS	DISTRICTS
17.10.2021	Isolated heavy to very heavy rainfall and Thunderstorm accompanied with Lightning/Hail & Squall(wind speed 60-70 KMPH gusting to 80 KMPH)	• Minor to medium landslides and rock falls at isolated places in vulnerable areas in hills. • Overflow of rivulets and streams at isolated places. • Minor to medium damages to kuccha houses and loose/unsecured structures due to squall. • Damage to livestock, crops, vehicles parked in open area due to hail.	• Settlements/People residing near the rivulets/streams are to remain cautious. • People are advised to be cautious and take shelter during thunderstorm/ hailstorm activities and during squall in safe places/Pucca houses. Take measures for livestock safety. • People are advised to park their vehicles at safe places/sheltered parking.	**ALERT**: Uttarkashi, Chamoli, Rudraprayag, Pithoragarh, Bageshwar, Dehradun, Tehri, Nainital, Haridwar and Udham Singh Nagar.
18.10.2021	Fairly widespread heavy to very heavy rainfall with extremely heavy rainfall at isolated places. and Thunderstorm accompanied with Lightning/Hail & Squall(wind speed 60-70 KMPH gusting to 80 KMPH)	• Minor to medium landslides and rock falls at isolated places in vulnerable areas. • Blocking/washout of highways/link roads and bridges at a few places in hills. • Overflow of rivulets and streams. Significant rise in water levels of major riviers. • Minor to medium damages to kuccha houses and loose/unsecured structures due to squall. • Uprooting of trees and breaking of branches. • Damage to livestock, crops, vehicles parked in open area due to hail/squall.	• People residing in vulnerable areas prone to landslides are to remain alert. • People are advised to avoid travelling. • Settlements/People residing near the riviers/rivulets/streams and low lying areas and flood plains are to remain alert. • People are advised to be cautious and take shelter during thunderstorm/ hailstorm activities and during squall in safe places/Pucca houses. Take measures for livestock safety. • People are advised to park their vehicles at safe places/sheltered parking. • Dam management/control authorities are advised to take necessary precautionary measures. • Mountaineering expeditions may be halted and the expedition members are advised to move to the safe places. • ***State government authorities are advised to take all necessary precautionary measures to control the movement and ensure safety of life of people.***	**TAKE ACTION**: Uttarkashi, Chamoli, Rudraprayag, Pithoragarh, Bageshwar, Nainital, Almora, Champawat, Dehradun, Tehri, Pauri, Haridwar, and Udham singh nagar.

Fig. 14. Special press release issued on 16th October regarding extremely heavy rainfall in Uttarakhand

mitigation measures. The forecasts at different lead time generated by the IMD have a significant role in pre, during and post-disaster operations. This can effectively be used for disaster prevention, mitigation & management purposes [Thapliyal, 2021]. Fig. 14 shows the warnings, expected impact and advisories issued by MC, Dehradun on 16th October, 2021. Based on these warnings the Disaster management authority of Government of Uttarakhand issued a warning letter and activated the Incidence Response System (IRS) for effective and comprehensive management of disaster response by various government and non-government stakeholders. Based on the extremely heavy rainfall warning input from Meteorological Centre, Dehradun, the state government authorities called a disaster preparation meeting under the chairmanship of Chief Minister of Uttarakhand and took a decision to suspend Char DhamYatra, movement of tourists & Pilgrims in hills and closed all educational institutions which resulted in less human life loss due to this unprecedented event.

4. Conclusion

(*i*) Under the influence of LPA over central India, the strong southeasterly winds (Atmospheric River) coming from BoB from 17th to 19th October provided a large amount of continuous moisture supply over the Kumaun region. The upper level divergence provided by the trough in mid and upper tropospheric westerlies as well as the blocking of Atmospheric River in mid and lower tropospheric levels by the WD and the Himalayas over the Kumaun region of Uttarakhand resulted in exceptionally heavy rainfalls. The environmental steering current associated with the trough in westerlies also caused the re-curvature of the LPA northwards and then northeastwards. The current and past studies of exceptionally heavy rainfall over western Himalayan region [Singh & Chand, 2015; Sikka *et al*., 2015; Chevuturi and Dimri, 2016; Yadav *et al*., 2017; Ghosh and Veeraraghavan, 1975] suggest the interaction of (1) the easterly system (lows or cyclonic circulations) laying over central or northwest India, (2) penetration of strong south easterly winds from BoB up to the mid-tropospheric levels which can be considered as atmospheric river causing enormous moisture incursion, (3) the deep mid & upper tropospheric westerly trough and (4) the Orography are favourable for exceptionally heavy rainfall over the zone of interaction in western Himalayan region.

(*ii*) The movement of western disturbance and the trough in westerlies was very slow from 16th to morning of 18th October and it moved very rapidly thereafter in next 24 hours. The upper-level divergence ($\geq 15\times10^{-5}s^{-1}$) and lower-level convergence ($\geq 5\times10^{-5}s^{-1}$) caused by the above synoptic systems over Uttarakhand are favourable for heavy rainfall.

(*iii*) The X-band DWR and AWS/ARG data suggest that the rainfall was of light to moderate intensity (10-20 mm/h) over most of the area and during most of the period. The rainfall intensity was extremely intense (50-100 m/hour) for around 1-hour duration in 7 stations of Udham Singh Nagar, Champawat, Nainital and Pauri districts. The reflectivity of the clouds was in the range of 20 to 40 dBZ at 99% of the time and 99% of the area covered by DWR during these 3 days. Unlike the June 2013 extremely heavy rainfall event over Uttarakhand which caused the extremely heavy rainfall over whole Uttarakhand state, this event was concentrated over the Kumaun region. According to the rain rate based rainfall intensity, the cloud burst ($R \geq 100$ mm/h) event was not observed at any station in Uttarakhand during this period.

(*iv*) Based on the above synoptic analysis and NWP model guidance the 17th to 19th October excessive rainfall event was forecasted 5 days in advance with good accuracy. The extreme rainfall of 18th October over Uttarakhand was predicted by the GFS (T-1534) and WRF NWP models with very good accuracy.

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References

ADGM (R), 2014, "Climate of Uttarakhand. Climatological summaries of states series - No. 21", Additional Director General of Meteorology (Research), 11.

ADGM (R), 2015, "Forecasting Circular No. 5/2015 (3.7)", ADGM(R)/UOI No. W-969, 7.

Chevuturi, A. and Dimri, A.P., 2016, "Investigation of Uttarakhand (India) disaster-2013 using weather research and forecasting model", *Natural Hazards*, **82**, 3, 1703-1726.

Das, S., 2013, "Uttarakhand tragedy", *Journal of the Geological Society of India*, **82**, 2, 201-201.

Ghosh, S. K. and Veeraraghavan, K., 1975, "Severe floods in Jammu & Kashmir in August I973", *MAUSAM*, **26**, 2, 203-207.

Lavers, D. A., Allan, R. P., Wood, E. F., Villarini, G., Brayshaw, D. J. and Wade, A. J., 2011, "Winter floods in Britain are connected to atmospheric rivers", *Geophysical Research Letters*, **38**, 23.

List, R., 1988, "A linear radar reflectivity-rainrate relationship for steady tropical rain", *Journal of Atmospheric Sciences*, **45**, 23, 3564-3572.

Marshall J. S. and Palmer W., 1948, "The distribution of raindrops with size", *J. of Meteor.*, **5**, 165-166.

Mishra, A., 2015, "Cloudburst and landslides in Uttarakhand : A natures fury?", *MAUSAM*, **66**, 1, 139-144.

Nandargi, S. and Dhar, O. N., 2012, "Extreme rainstorm events over the northwest Himalayas during 1875-2010", *Journal of Hydrometeorology*, **13**, 4, 1383-1388.

Nandargi, S., Gaur, A. and Mulye, S. S., 2016, "Hydrological analysis of extreme rainfall events and severe rainstorms over Uttarakhand, India", *Hydrological Sciences Journal*, **61**, 12, 2145-2163.

Pai, D. S., Bandgar, A., Devi, S., Musale, M., Badwaik, M. R., Kundale, A. P., Gadgil, S., Mohapatra, M. and Rajeevan, M., 2020, "New normal dates of onset/progress and withdrawal of southwest monsoon over India", *MAUSAM*, **71**, 4, 553-570.

Rao M. S. V., Srinivasan V.and Raman S., 1970, "Discussion of typical synoptic weather situations: Southwest Monsoon-Typical Situations Over Northwest India. Forecasting Manual, III-3.3", The Deputy Director General of Observatories (Forecasting), Poona-5.

Rao, P. C., Archana, S. and Jaswal, A. K., 2016, "Intense precipitation causing floods over Himalayan region of northern India–a case study on role of atmospheric rivers", *J. Ind. Geophys. Union*, **20**, 2, 191-200.

Satendra, Anandha Kumar K. J. and Naik, V. K., 2014, "India Disaster Report2013", *National Institute of Disaster Management*, 2014, p19.

Sati, V. P., 2013, "Extreme weather related disasters: A case study of two flashfloods hit areas of Badrinath and Kedarnath valleys, Uttarakhand Himalaya, India", *Journal of Earth Science and Engineering*, **3**, 8, p562.

Sikka, D. R., Ray, K., Chakravarthy, K., Bhan, S. C. and Tyagi, A., 2015, "Heavy rainfall in the Kedarnath valley of Uttarakhand during the advancing monsoon phase in June 2013", *Current Science*, 353-361.

Singh, C. and Chand, R., 2015, "Exceptionally heavy rainfall over Uttarakhand during 15-18 June, 2013-A case study", *MAUSAM*, **66**, 4, 741-750.

Steiner, M., Smith, J. A. and Uijlenhoet, R., 2004, "A microphysical interpretation of radar reflectivity-rain rate relationships", *Journal of the atmospheric sciences*, **61**, 10, 1114-1131.

Thapliyal, R., 2021, "Role of Weather Advisory Services in Disaster Prevention, Mitigation and Management",Disaster - Response and Management Volume VIII, Issue-1, (ISSN: 2347-2553), 68-77.

Yadav, B. P., Kumar, N. and Lotus, S., 2017, "Synoptic & climatological aspects of extreme rainfall over western Himalayas towards end of 2014 southwest monsoon season", *MAUSAM*, **68**, 4, 597-606.