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Cloudburst events observed over Uttarakhand during monsoon season 2017 and their analysis

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सार – बादल फटना एक चरम मौसम की घटना है जो एक छोटे से क्षेत्र में एक घंटे में 100 मिमी या अधिक की वर्षा के साथ एक छोटे से क्षेत्र में बड़ी मात्रा में वर्षा की घटना की विशेषता है। यह अचानक बाढ़, निचले इलाकों में बाढ़ और पहाड़ियों में भूस्खलन के लिए जिम्मेदार है, जिससे जान-माल की व्यापक क्षति होती है। मॉनसून सीजन 2017 के दौरान उत्तराखंड में पांच बादल फटने की घटनाएं देखी गई हैं और उनका विश्लेषण किया गया है। सेल्फ रिकॉर्डिंग रेन गेज (SRRG) और नए स्थापित जनरल पैकेट रेडियो सर्विस (GPRS) आधारित ऑटोमैटिक वेदर स्टेशन (AWS) से 15 मिनट के अंतराल के डेटा उत्तराखंड के कुछ क्षेत्रों में बादल फटने की घटनाओं को पकड़ने में सक्षम हैं। इस पत्र में , उत्तराखंड में बादल फटने की घटनाओं की घटना से जुड़ी महत्वपूर्ण पर्यायवाची और थर्मोडायनामिक स्थितियों का पता लगाने का प्रयास किया गया है। उत्तराखंड में जून , जुलाई और अगस्त 2017 के महीने के दौरान कैप्चर की गई बादल फटने की घटनाओं के ये 5 मामले हैं विस्तार से अध्ययन किया। पर्यायवाची रूप से, यह देखा गया है कि पंजाब से लेकर उत्तराखण्ड के निकट बंगाल की खाड़ी की ओर जाने वाले समुद्र तल पर ट्रफ का अस्तित्व, उत्तरी पाकिस्तान और उससे सटे जम्मू-कश्मीर पर पश्चिमी विक्षोभ की गति और उत्तरी राजस्थान और पड़ोस पर चक्रवाती परिसंचरण का अस्तित्व अनुकूल है। शर्तें। इसके अलावा , इन घटनाओं के दौरान ऊपरी हवा चार्ट पर पश्चिमी राजस्थान और हरियाणा में अरब सागर से मजबूत दक्षिण -पश्चिम हवा की उपस्थिति पाई जाती है। थर्मोडायनामिक रूप से, संवहनी उपलब्ध संभावित ऊर्जा (सीएपीई) अधिकांश मामलों के दौरान उच्च (1100 जे/केजी से अधिक) पाई जाती है और लंबवत एकीकृत प्रारंभिक जल सामग्री (पीडब्ल्यूसी) 55 मिमी से अधिक है। जीपीआरएस आधारित एडब्ल्यूएस प्रणाली राडार उत्पादों के सहयोग से आधे से एक घंटे तक के लीड समय के साथ निर्दिष्ट स्थान पर बादल फटने की घटना की भविष्यवाणी करने में मदद कर सकती है।

ABSTRACT. Cloudburst is an extreme weather event characterised by the occurrence of a large amount of rainfall over a small area within a short span of time with a rainfall of 100 mm or more in one hour. It is responsible for flash flood, inundation of low lying areas and landslides in hills causing extensive damages to life and property. During monsoon season 2017 five number of cloudburst events are observed over Uttarakhand and analysed. Self Recording Rain Gauge (SRRG) and 15 minutes interval data from the newly installed General Packet Radio Service (GPRS) based Automatic Weather Station (AWS) are able to capture the cloudburst events over some areas in Uttarakhand. In this paper, an attempt has been made to find out the significant synoptic and thermodynamic conditions associated with the occurrence of the cloudburst events in Uttarakhand. These 5 cases of cloudburst events that are captured during the month of June, July and August 2017 in Uttarakhand are studied in detail. Synoptically, it is observed that the existence of trough at mean sea level from Punjab to head Bay of Bengal running close to Uttarakhand, the movement of Western Disturbance over north Pakistan and adjoining Jammu & Kashmir and existence of cyclonic circulation over north Rajasthan and neighbourhood are favourable conditions. Also, the presence of strong south-westerly wind flow from the Arabian Sea across West Rajasthan and Haryana on upper air charts are found during these events. Thermodynamically, the Convective Available Potential Energy (CAPE) is found to be high (more than 1100 J/Kg) during most of the cases and vertically integrated precipitable water content (PWC) is more than 55mm. The GPRS based AWS system can help in prediction of the cloud burst event over the specified location with a lead time upto half to one hour in association with radar products.

Key words – Cloudburst, Air mass, AWS, SRRG, CAPE, Western disturbance.

1. Introduction

The state of Uttarakhand, due to its geographical location, is extremely vulnerable to natural disasters. Every year the state suffers a great loss to lives and properties due to natural hazards, like earthquakes, landslides, avalanches, hailstorms, Glacial Lake Outburst Floods (GLOFs) & flash floods associated with or without cloudbursts, lightning and forest fires, etc. One of the most severe natural disasters in recent decades is Uttarakhand flash floods due to cloud burst in June 2013. 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 spatial and temporal scale of cloud burst events is very small and therefore most of the cloud burst events are reported based on their effect experienced in terms of loss to life and property. There are a very few studies carried out on understanding of these events. Caine (1980) established and later updated by Guzzetti *et al*. (2008), the threshold value of minimum rainfall duration and intensity required to trigger shallow landslides and debris flows. Many studies (Dahal & Hasegawa 2008; Gabet *et al*., 2004; Sengupta *et al*., 2010; Shekhar *et al*., 2015; Rao *et al*., 2020) on Himalayan region also showed that seasonal accumulation and a daily total rainfall threshold must overcome before the landslides are initiated. As it is difficult to record actual rainfall with existing rain gauge network, many studies (Bhan *et al*., 2015; Bhatt *et al*., 2011; Sravan Kumar *et al*., 2012) used satellite data to estimate the total accumulated rainfall during cloudburst over a region. A number of studies have been carried in the past to understand the synoptic and mesoscale environments conducive for heavy Orographic rainfall in Rockies and Appalachians region of USA (Maddox *et al*., 1980; Petersen *et al*., 1999); the European Alps (Massacand *et al*., 1998); the Western Ghats in India (Smith *et al*., 1997) and other regions. In this paper, an attempt has been made to understanding the exact mechanism of the driving processes of cloudbursts in Uttarakhand using actual rainfall data.

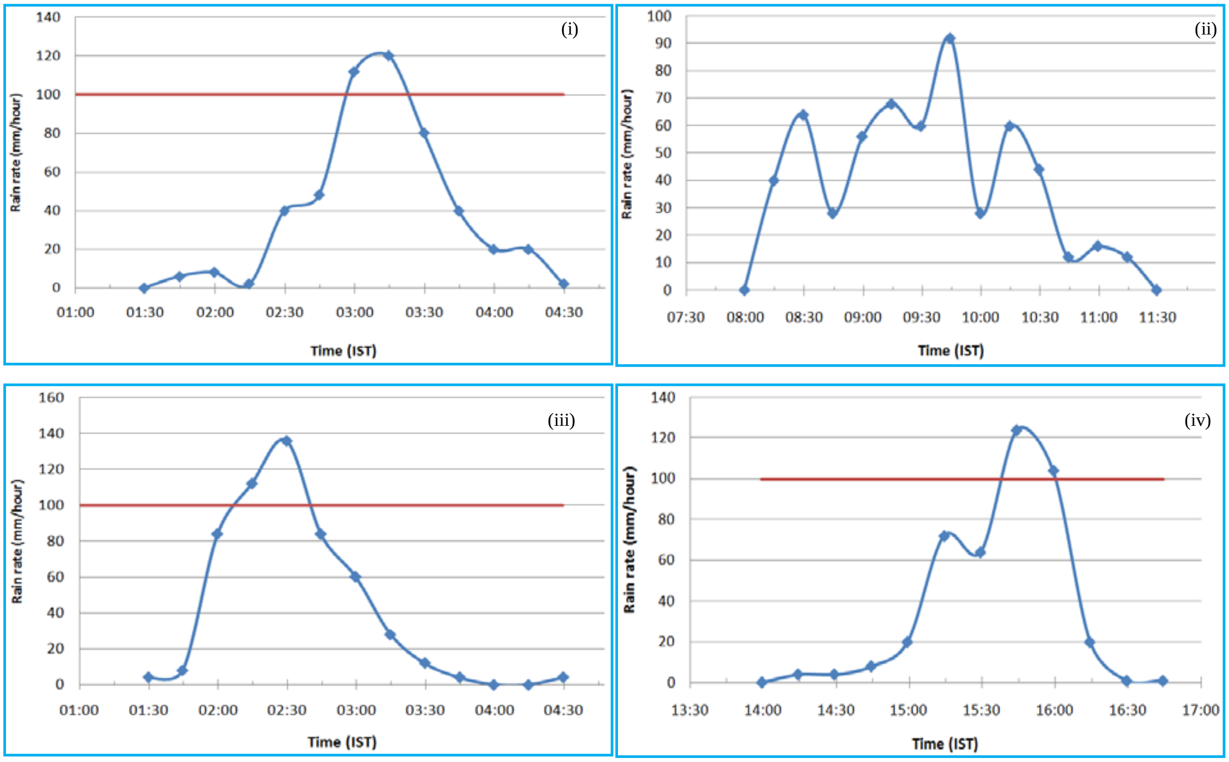
Uttarakhand is situated along latitude 30°N, the boundary of tropical and the subtropical zones where two different air masses interact with each other occasionally during monsoon season. The Orography (Andermann *et al*., 2011; Houze *et al*., 2007; Singh & Kumar, 1997) of the region in association with the favourable synoptic and thermodynamic conditions is conducive for the occurrence of heavy downpour/cloudburst events. The interaction of tropical and subtropical air masses is relatively more prominent over Uttarakhand during the advance and initial phases and the retreating phase of the southwest monsoon season. Due to very small spatial and temporal scale of the cloudburst event, it is very difficult to observe and forecast the occurrence with the help of conventional observational and forecasting techniques or predicting it with the global & regional Numerical Weather Prediction (NWP) models. In this paper, 5 cases of cloudburst events that occurred during the monsoon season 2017, *viz*., on 26th June over Dehradun, 29th June over Roorkee, 12th July over Dehradun, 20th July over Jaspur and 3rd August over Dehradun in Uttarakhand are studied extensively. In most of the cases of observed cloudburst events, the rainfall is observed upto 100mm/h. However, different definitions of cloudburst are used, *e.g*., the Swedish weather service, Swedish Meteorological and Hydrological Institute (SMHI), defines the corresponding Swedish term "Skyfall" as 1 mm/min for short bursts and 50 mm/hour for longer rainfalls ("Skyfallochrotblöta", 2011).

In Uttarakhand, it is observed that a rainfall amount of 50 mm/hour for short duration is able to cause landslide and flash floods in hills. The 50 mm rainfall per hour may be considered as a threshold for cloudburst in hilly terrains of Uttarakhand. Kanungo & Sharma (2014) showed that a rainfall intensity of 0.87 mm/h poses a high risk of landslide in Chamoli-Joshimath region for rainfall events of less than 24-hourduration. Also, a minimum 10-day and 20-day antecedent rainfall of 55 mm and 185 mm respectively are the threshold for the initiation of landslides.

2. Data and methodology

Self-Recording Rain Gauge (SRRG) and newly installed General Packet Radio Service (GPRS) based Automatic Weather Stations' (AWS) rainfall data of Dehradun and Jaspur stations are used for the study. Till 2017 around 16 AWSs in Uttarakhand are upgraded with GPRS based communication system which provides meteorological data at an interval of 15 minutes and is more efficient (Houghton-Carr, 2009) than older satellite-based communication system; which causes loss of data bursts due to collision (Muthuramlingam *et al*., 2006). Due to GPRS based communication, the transmission of data from AWS systems have become much easier and more frequent and is helpful in capturing, monitoring and nowcasting the cloudburst events.

Dehradun is situated in a valley between the Shivaliks and the Himalayas, therefore, the lower level winds do not correctly represent the general wind circulation. However, Patiala is situated on the same latitude of 30.3 °N as that of Dehradun and is around 160 km west of Dehradun. Sincethe area of coverage of RS/RW is large ("Guide To The GCOS Surface", 2010) and homogeneity of Patiala station with the Dehradun station in terms of geographical position, the daily RS/RW data of 0000 UTC of Dehradun and Patiala stations are used for the atmospheric sounding information. On 3rd August, 2017 there was no ascent from the Patiala station, therefore, RS/RW data from Dehradun station is used for the study. Satellite images and S-band & C-band Doppler weather radar images from Patiala and Delhi stations respectively are used to study the movement and nature of cloud mass responsible for the cloudburst events. In



Figs. 1(i-iv). Rainfall intensity curve of cloudburst events that occurred over Uttarakhand (i) Dehradun on 26th June, 2017 (ii) Dehradun on 12th July, 2017 (iii) Jaspur on 20th July, 2017 (iv) Dehradun on 3rd August, 2017

addition, all India surface and upper air charts are analysed to find out the favourable synoptic situations associated with the cloudburst events.

Thermodynamic indices are calculated based on the 0000 UTC RS/RW data from Patiala and Dehradun stations. The Convective Available Potential Energy (CAPE) is used to deduce the general instability present in the atmosphere. CAPE is not attached to any pressure levels which makes it more usable for uneven topography of Uttarakhand. CAPE is calculated by

$$\text{CAPE} = g\int_{\text{LFC}}^{\text{EL}} \frac{T_p - T_e}{T_e}\,dz,$$

where, g is the acceleration due to gravity, LFC is the level of free convection and EL is the equilibrium level of the air parcel, T_p is the temperature of the air parcel when raised dry adiabatically from the surface to Lifting condensation level (LCL)and moist adiabatically thereafter and T_e is the temperature of the environment. The lifted index (LI) is used to determine the thermal instability of atmosphere at 500 hPa level. LI (Galway, 1956) is calculated by

$$\text{LI} = T_{500} - T_p,$$

where, T_{500} is temperature in degree Celsius of the environment at 500 hPa and T_p is 500 hPa temperature in degree Celsius of a lifted parcel from the surface.

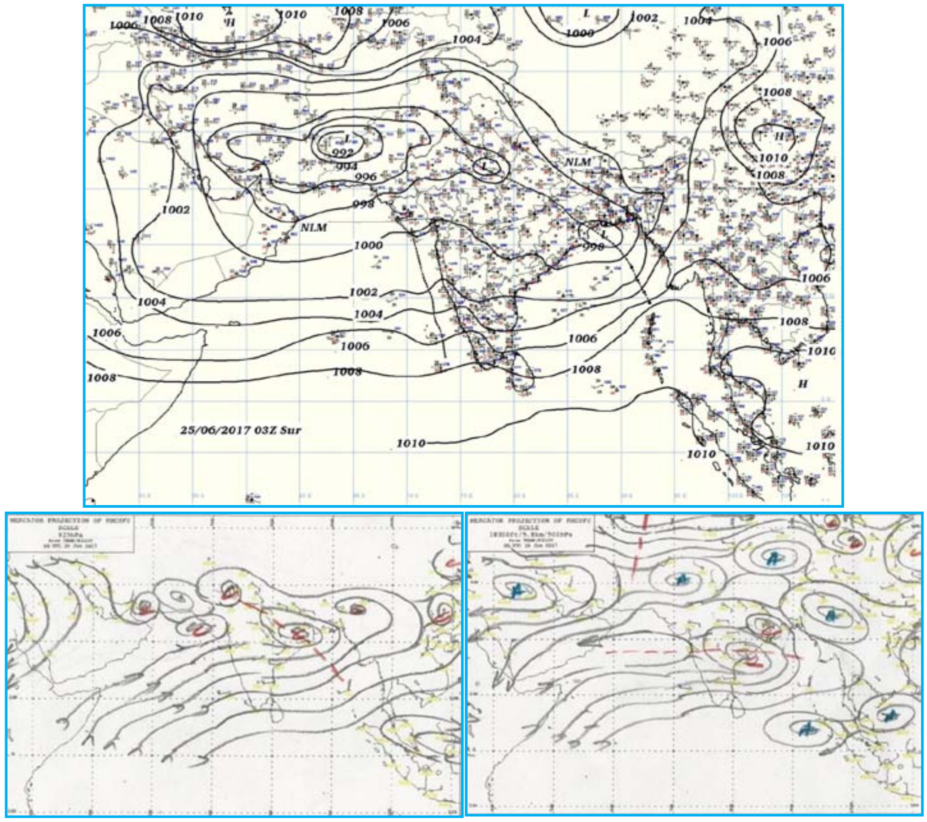
Severe Weather Threat Index (SWEAT) determines the potential for severe weather by incorporating multiple parameters like low-level moisture (850 hPa dewpoint), lower and middle-level (850 and 500 hPa) wind speeds, Total Totals Index and warm air advection (veering between 850 and 500 hPa). SWEAT index as defined by Miller (1972) is:

$$\text{SWEAT} = 12 * T_{d850} + 20 * \beta + 2 * V_{850} + V_{500} + 125 * [\sin(\alpha_{500} - \alpha_{850}) + 0.2] \text{ and}$$

$$\beta = \text{Max}\,\{[(T_{850} - T_{500}) + (T_{d850} - T_{500})], 0\}$$

where, T_{d850} is Dewpoint temperature in degree Celsius at 850 hPa, T_{850} & T_{500} are temperatures in degree Celsius at 850 hPa & 500 hPa, T_{850} & T_{500} are 850 hPa & 500 hPa wind speed in knots and α_{500} & α_{850} are Wind direction at 500 & 850 hPa level.

The rainfall data from GPRS based AWS, radar & satellite observations and upper air atmospheric profile from RS/RW is very useful for forecaster in nowcasting of cloudburst events.



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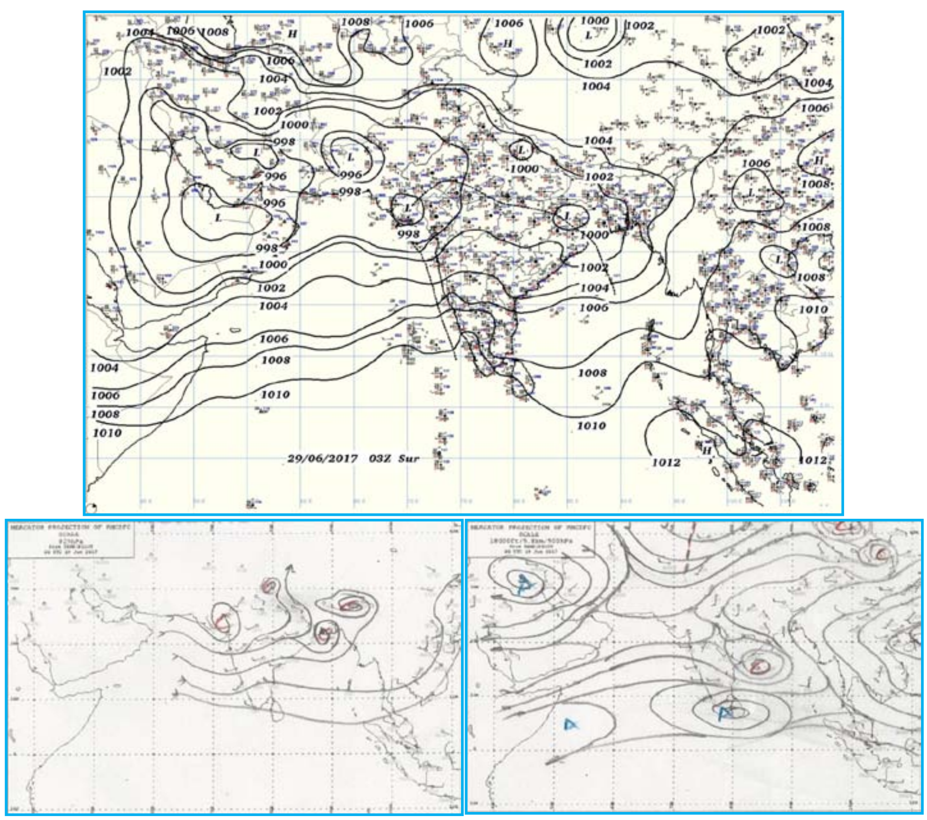

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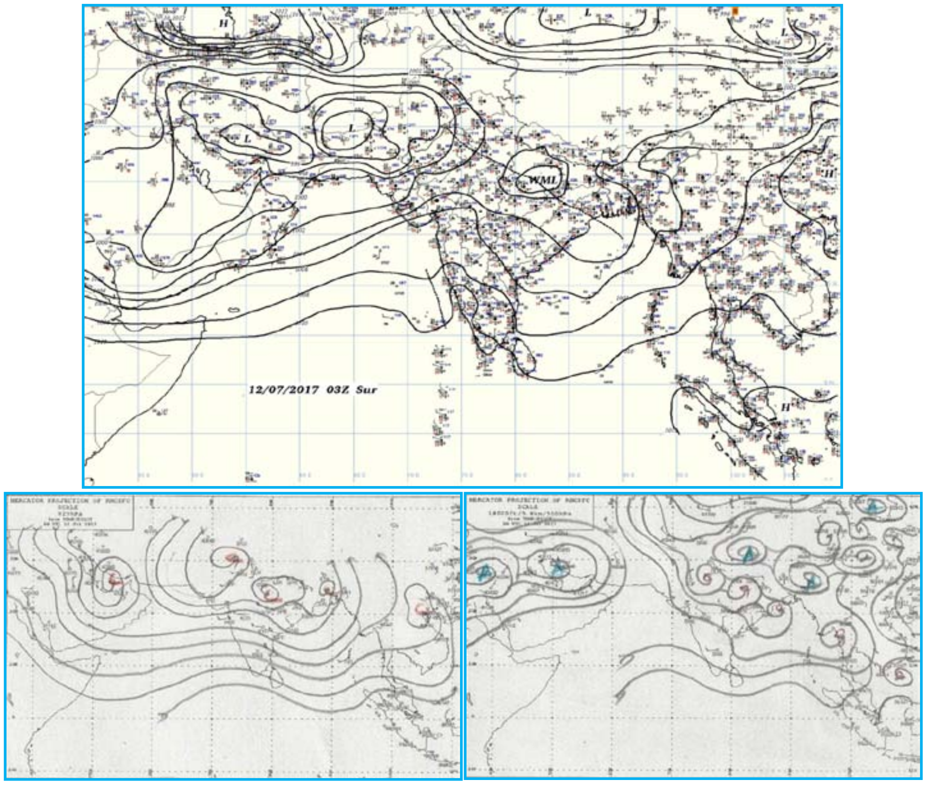
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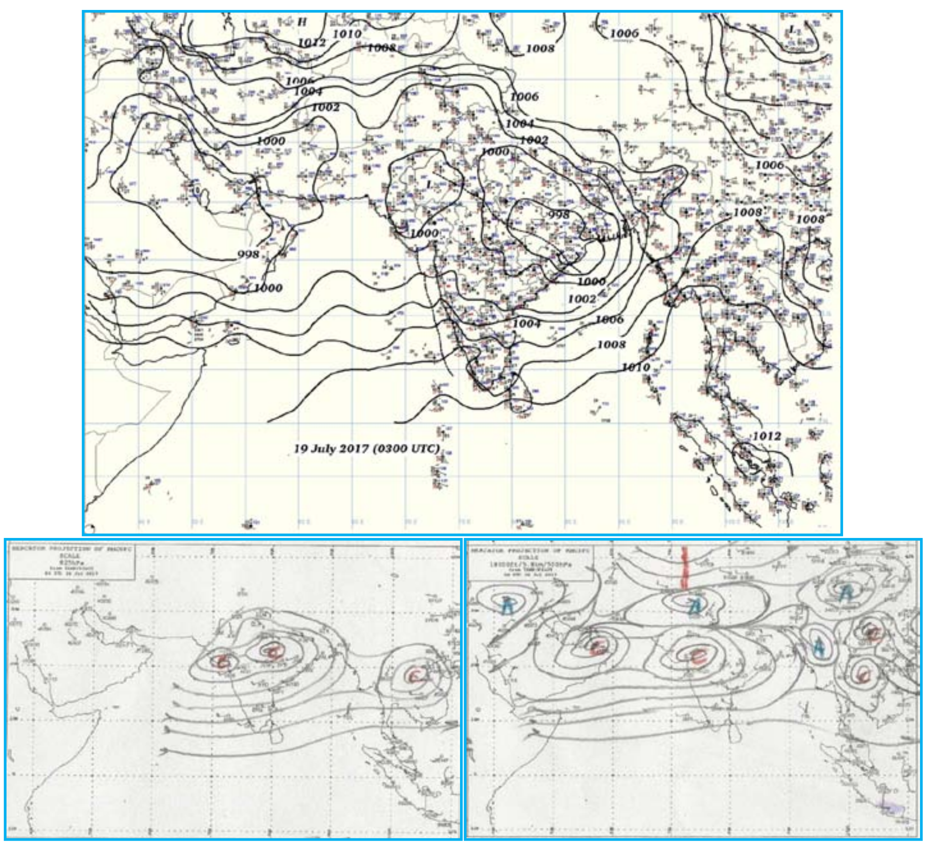
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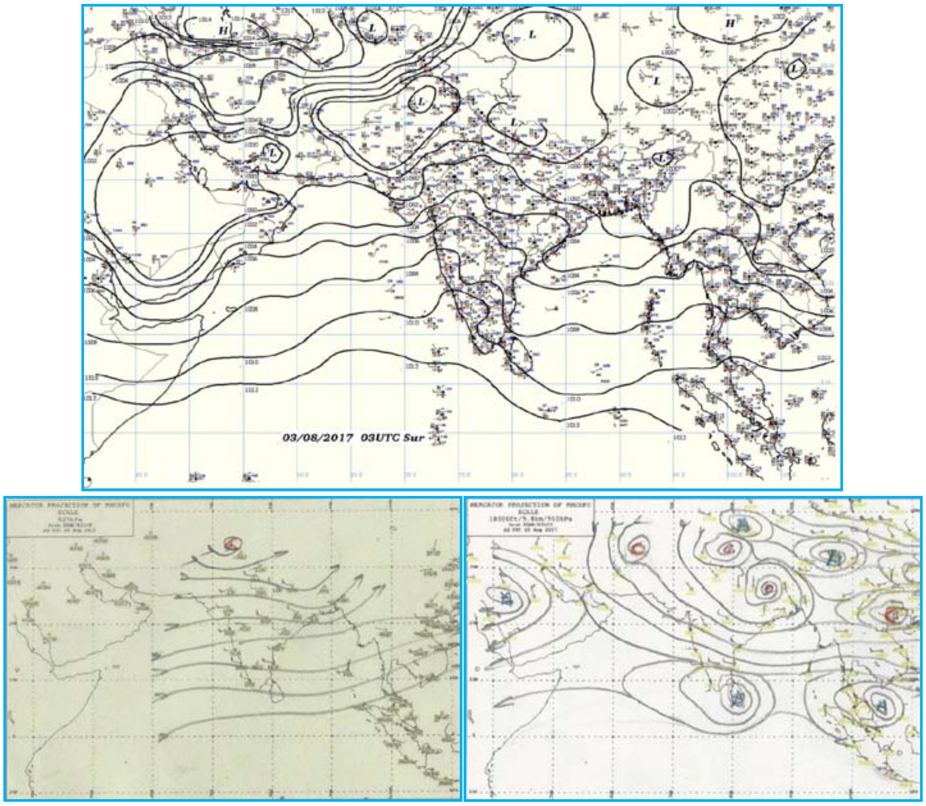


(v)

Figs. 2(i-v). Analysed surface and 925 & 500 hPa level upper air charts of the cloudburst events on (i) 26th June, 2017 over Dehradun. The surface chart is based on 0300 UTC synoptic observations on 25th June, (ii) 29th June, 2017 over Roorkee, (iii) 12th July, 2017 over Dehradun (iv) 20th July, 2017 over Jaspur. The surface chart is based on 0300 UTC synoptic observations on 19th July and (v) 3rd August, 2017 over Dehradun

3. Results and discussion

All the cloudburst events studied during the period occurred over a region lying in the foothills of the Himalayas showing homogeneity of the regions in terms of proximity to the mountains and the timeline of the cloudburst events over Uttarakhand shows that the early morning/morning hours are most conducive for the occurrence. Based on the State Emergency Operations Center, Uttarakhand State Disaster Management Authority's daily report, these severe weather events caused a loss of 2 human lives, 18 animal lives and severe damage to 1 house. These events also caused water-logging and minor landslides in the region.

3.1. *Synoptic Analysis of cloudburst event over Dehradun on 26th June, 2017*

The cloudburst occurred over Dehradun during the early morning hours on 26th June, 2017. The 24 hour observed rainfall over the station was 143.7mm and 177.5mm measured with SRRG and Ordinary Rain Gauge (ORG) respectively. The difference of 33.8mm rainfall may be attributed to the wastage during the syphoning process of SRRG. The spell of extremely intense rainfall (between 50-100 mm/hour) started at 0230 IST and continued till 0415 IST on 26th June with more than 100 mm rainfall recorded in one hour between 0230 IST and 0330 IST. The rain rate was more than 110 mm/hour between 0300 IST to 0330 IST. Fig. 1 (i) shows the rainfall intensity curve generated from the 15 minutes interval data from the SRRG chart.

The synoptic analysis of 0300 UTC surface and upper air charts showed the presence of a trough at mean sea level from West Rajasthan to the north Andaman Sea on 25th June and from West Rajasthan to east central Bay of Bengal across north Madhya Pradesh, Chhattisgarh and Jharkhand extending upto 1.5 km above mean sea level on 26th June 2017. An upper air cyclonic circulation also laid over south Pakistan & neighbourhood on 25th June and over south Pakistan & adjoining Kutch extending upto 0.9 km above mean sea level on 26th June. A western disturbance as a trough in mid-tropospheric westerlies

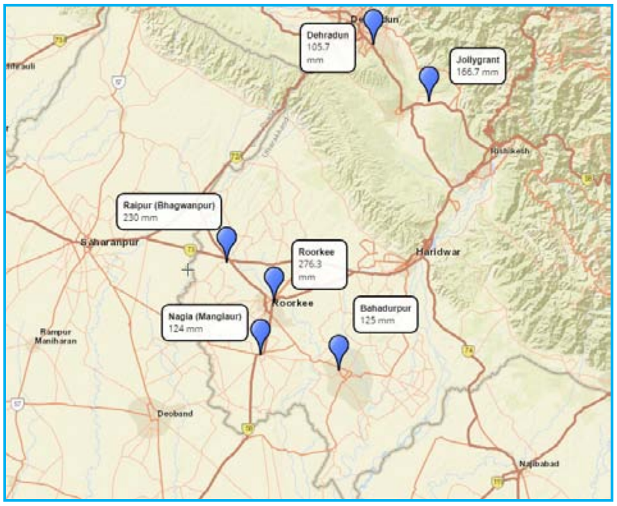


Fig. 3. Centre of the cloudburst event on 29th June, 2017

with its axis at 5.8 km above mean sea level ran roughly along longitude 64.0° E and north of latitude 30.0° N on 26th June and along longitude 66.0° E and north of latitude 28.0° N on 27th June, 2017. Fig. 2(i) shows the analysed upper air charts of 26th June at 0000 UTC.

3.1.1. *Synoptic analysis of cloudburst event over Roorkee on 29th June, 2017*

Two days after the cloudburst event over Dehradun another event occurred over Roorkee on 29th June, 2017 with extremely intense rainfall spell between 0800 IST and 1200 IST. The amount of 24 hours accumulated rainfall measured in Dehradun was 101.4mm and 105.7 mm from SRRG and ORG respectively. The 24 hour accumulated rainfall reported from other stations was 124 mm from Nagla (Manglaur), 125 mm from Bahadurpur, 166.7 mm from Jollygrant, 230 mm from Raipur (Bhagwanpur) and 276.3 mm rainfall within around 2 hours from Roorkeewhich wasthe centre of the cloudburst event (Fig. 3). Roorkee was flooded on the day.

The 0300 UTC synoptic analysis [Fig. 2(ii)] showed the presence of a low-pressure area over Saurashtra and neighbourhood and associated upper air cyclonic circulation extended upto 4.5 km above mean sea level on 29th June. A trough at mean sea level ran from the centre of a low-pressure area over Saurashtra & neighbourhood to west central Bay of Bengal across north Madhya Pradesh, Chhattisgarh and north Odisha extending up to 1.5 km above mean sea level on 29th June. A western disturbance as a trough in mid-tropospheric westerlies with its axis at 5.8 km above mean sea level ran roughly along longitude 66.0° E and north of latitude 28.0°N on

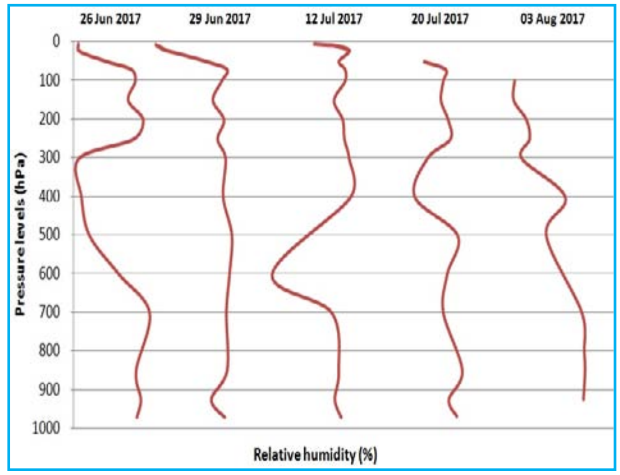


Fig. 4. Vertical moisture profile of atmosphere during five cloudburst events

28th June and along longitude 71.0° E and north of latitude 30.0° N on 29th June, 2017.

3.1.2. *Synoptic analysis of cloudburst event over Dehradun on 12th July, 2017*

The rainfall on 12th July, 2017 started at 0730 IST and continued till 1130 IST over Dehradun with the extremely intense spell between 0830 to 0945 IST with an average rain rate of more than 60 mm/hour as shown in Fig. 1 (ii). The 4 hours accumulated rainfall recorded at Dehradun observatory was 146 mm and at AWS Dehradun was 145 mm. The centre of the cloud mass was southwest to south of the observatories [Fig. 7 (iii)].

The 0300 UTC synoptic analysis [Fig. 2(iii)] showed the presence of a trough at mean sea level from Punjab to northwest Bay of Bengal across centre of low pressure area over East Uttar Pradesh, Jharkhand and Gangetic West Bengal on 11th July and from northwest Rajasthan to northwest Bay of Bengal across centre of well-marked low pressure area over east Uttar Pradesh, Jharkhand and Gangetic West Bengal on 12th July. An upper air cyclonic circulation laid over West Rajasthan & neighbourhood extending between 3.6 km and 5.8 km on 11th July and laid over northeast Rajasthan & neighbourhood at 5.8 km above mean sea level on 12th July. A fresh western disturbance as an upper air cyclonic circulation laid over north Pakistan & neighbourhood between 3.1 & 4.5 km above mean sea level on 12th July.

3.1.3. *Synoptic analysis of cloudburst event over Jaspur on 20th July, 2017*

On 20th July, 2017, the cloudburst over Jaspur occurred between 0145 IST and 0245 IST with the

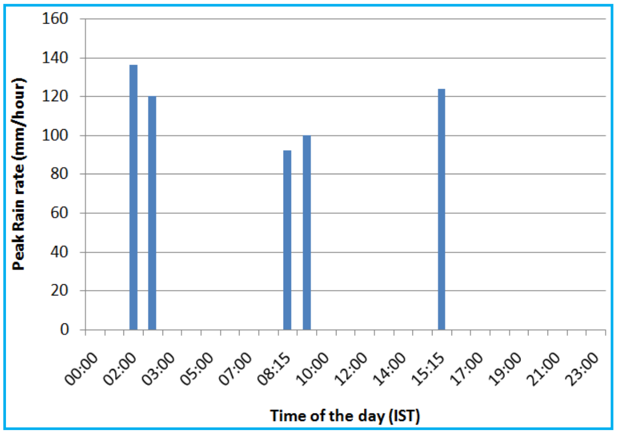


Fig. 5. Temporal distribution of the occurrence of cloudburst events within a day and the intensity of the associated rainfall

maximum accumulated rainfall of 104mm in one hour based on 15-minute interval data from GPRS based AWS. However, the extremely intense rainfall spell was observed between 0130 IST to 0330 IST with the maximum rainfall rate of 136 mm/hour between 0215 IST and 0230 IST as shown in Fig. 1 (iii). The synoptic analysis showed [Fig. 2(iv)] the presence of a low-pressure area over East Madhya Pradesh & neighbourhood on 19th July and over central parts of north Madhya Pradesh with associated upper air cyclonic circulation extending upto 3.1 km above mean sea level on 20th July. The axis of monsoon trough at mean sea level ran from southwest Rajasthan to east central Bay of Bengal on 19th July. An upper air cyclonic circulation laid over central parts of Rajasthan & neighbourhood and extending upto 1.5 km above mean sea level on 20th July. A western disturbance as an upper air cyclonic circulation laid over north Pakistan & adjoining Afghanistan at 3.1 km above mean sea level with the trough aloft with its axis at 5.8 km above mean sea level roughly along longitude 70.0 °E and north of latitude 32.0 °N on 19th July and along longitude 72.0 °E and north of latitude 34.0 °N on 20th July.

3.1.4. *Synoptic analysis of cloudburst event over Dehradun on 3rd August, 2017*

The rainfall started in the afternoon hours of 3rd August, 2017 with the extremely intense rainfall spell starting at 1500 IST and continuing till 1600 IST. The maximum rainfall rate of 114 mm/hour was recorded for half an hour between 1530 to 1600 IST. Fig. 1 (iv) shows the rainfall intensity curve generated from the 15 minutes interval data from GPRS based AWS at Dehradun station.

The synoptic analysis [Fig. 2(v)] reveals that the axis of monsoon trough at mean sea level ran through

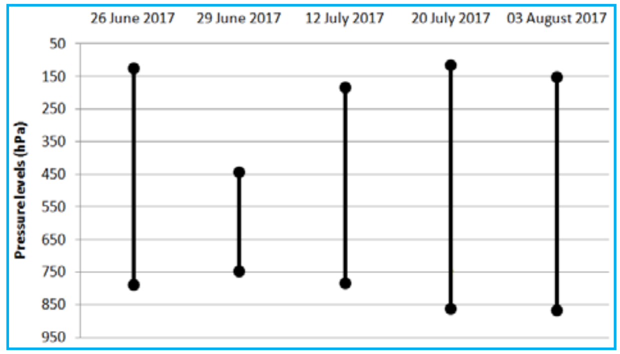


Fig. 6. The Vertical extent of clouds during cloud burst events

Amritsar, Karnal, Bareilly, Gorakhpur, Purnea, Malda and thence eastwards to East Assam on 2nd August; it shifted northwards on 3rd August and ran close to the foothills of Himalaya. An upper air cyclonic circulation laid over northern parts of central Uttar Pradesh & neighbourhood on 2nd August and laid over East Uttar Pradesh & adjoining Bihar between 3.6 & 5.8 km above mean sea level on 3rd August. A Western Disturbance as an upper air cyclonic circulation laid over central parts of Pakistan & adjoining area of Punjab on 2nd August and over Jammu & Kashmir & neighbourhood at 3.1 km above mean sea level on 3rd August.

3.2. *Thermodynamic conditions during cloud burst events*

Many studies (Chaudhuri & Bhowmick, 2006; Srivastava & Ray, 1999) suggest the role of CAPE in the occurrence of deep convection and severe thunderstorm. Srivastava & Ray (1999) analysed the occurrence of convective activities during April month over India and linked higher values of CAPE and smaller values of CINE to increased convective activities in India. Also, other stability indices like LI, SWEAT and precipitable water content are found to be a very good indicator of deep convection and are useful in forecasting thunderstorms (Agnihotri, 2014; Duraisamy *et al.*, 2011; Karmakar & Alam, 2006).

In this study, the CAPE values are found to be high ≥ 1100 J/kg and the LI are highly negative with values less than -3.6°C on three out of five cases of cloudburst events. The CAPE and LI values on 19th July were 2082 J/kg and -5.3°C respectively. The CAPE increased and LI decreased further till the morning of 20th July. The maximum CAPE and lowest LI values were observed on 20th July, 2017 as 3051 J/kg and -6.7°C respectively which caused cloudburst in Jaspur. The SWEAT index is high and greater than 255 for all the cases. Table 1(i) shows the observed values of the thermodynamic indices during the cloudburst events discussed above.

TABLE 1

(i) Observed thermodynamic parameters during thecloudburst events

Region of cloudburst	Date	CAPE (J/Kg)	Vertically integrated PWC (mm)	Lifted index	SWEAT index
Dehradun	26 Jun, 2017	2412.09	56.85	-5.58	261.21
Roorkee	29 Jun, 2017	106.44	66.89	-1.44	291.81
Dehradun	12 Jul, 2017	1119.33	53.65	-3.63	255.37
Jaspur	20 Jul, 2017	3051.43	65.26	-6.69	266.6
Dehradun*	3 Aug, 2017	327.89	59.29	-0.71	271.21

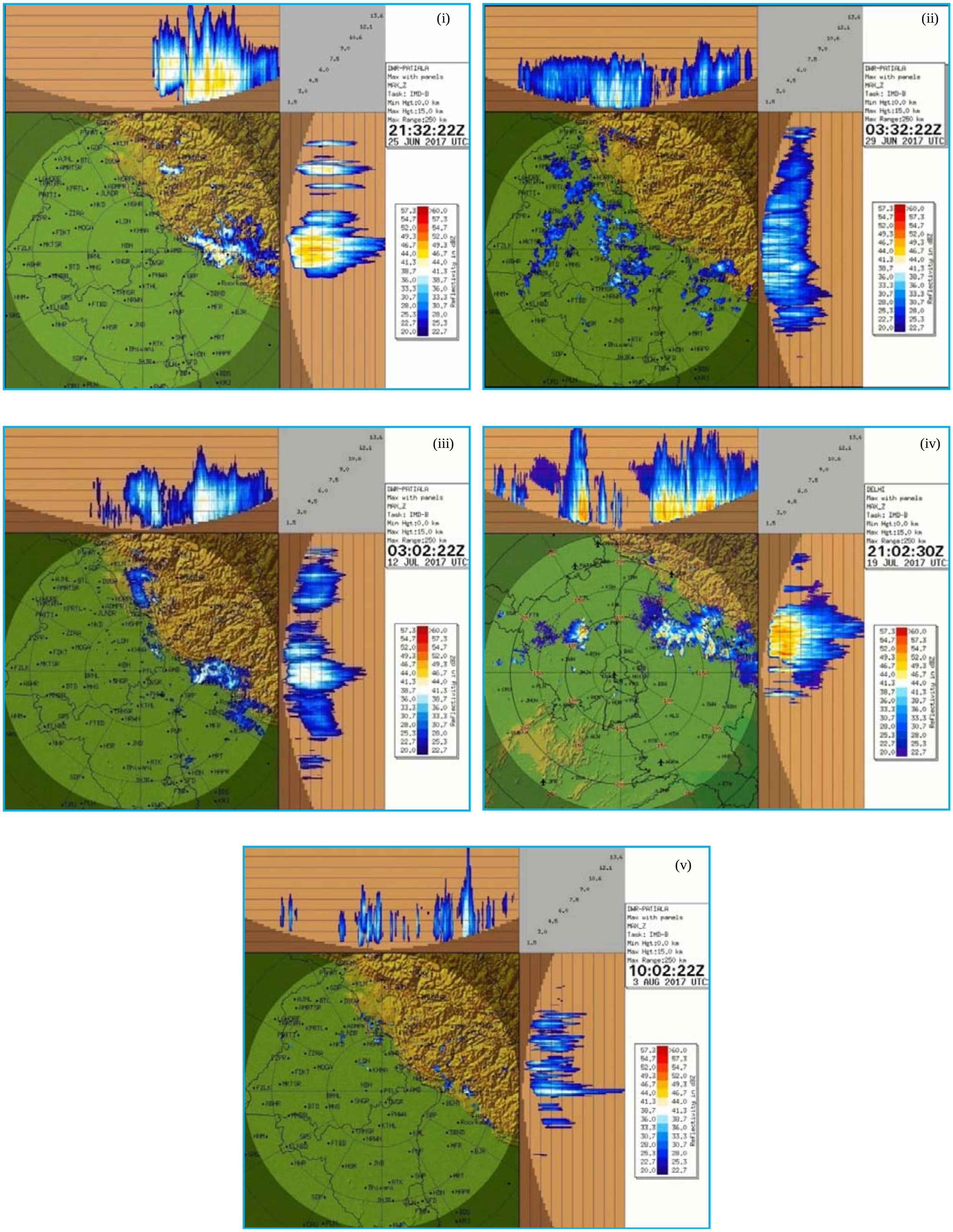
(ii) Observed wind parameters during the cloudburst events

Region of cloudburst	Date	Average direction of wind between 950 to 850 hPa (8 point compass)	Average wind speed between 950 to 850 hPa (knots)
Dehradun	26 Jun, 2017	South-easterly	21.6
Roorkee	29 Jun, 2017	Southerly	18.2
Dehradun	12 Jul, 2017	South-easterly to South-westerly	9
Jaspur	20 Jul, 2017	South-easterly	12
Dehradun*	3 Aug, 2017	Westerly	7

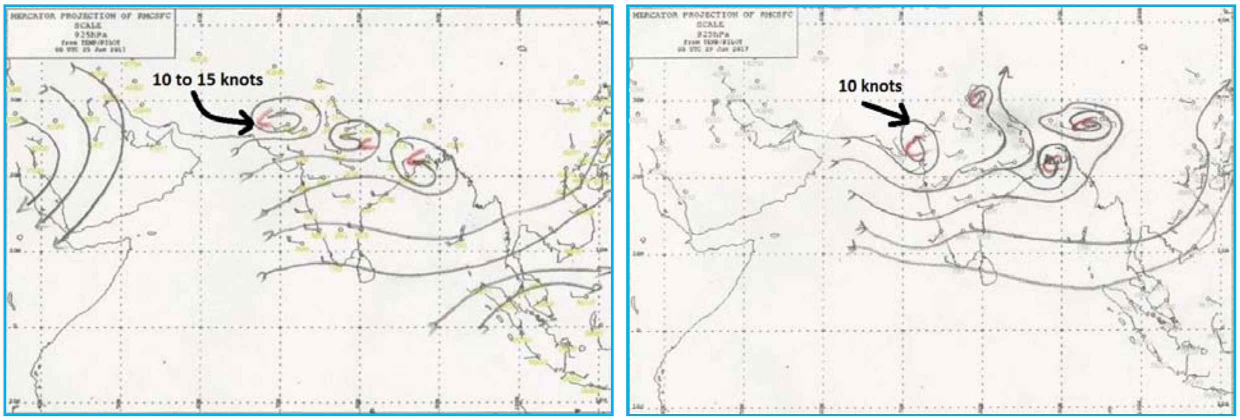
* 0000 UTC RS/RW observation on 3rdAug, 2017 is taken from Dehradun station, rest of the other RS/RW observations are taken from Patiala station.

For a large amount of rainfall within a small span of time, a substantial amount of moisture must be present in the atmosphere. The total precipitable water content (PWC) in the column of the air from the surface to 100 hPa is very high and greater than 53 mm in all the cloudburst cases. Also, the study of the vertical moisture profile during these events showed the existence of moisture in the lower and upper troposphere and relatively drier middle troposphere (Fig. 4). Roca *et al*. (2005) showed that the dry air in the mid-troposphere along with other favourable dynamic and thermodynamic parameters is necessary conditions for strong and long-lived convective systems. In cloudburst event on 26th June, 2017, the average relative humidity (RH) is less than 15% between 500 to 300 hPa pressure levels, but around 75% and 70% between the surface to 600 hPa and between 250 to 70 hPa pressure levels respectively. On 12th July, 2017, the RH is 1% to 14% between 700 to 400 hPa and around 80% and 90% in lower and upper troposphere respectively. Similarly, on 20th July, 2017, the average RH is around 80%, 30% and 70% between the surface to 450 hPa, between 450 to 300 hPa and above 300 hPa respectively. There is frequent variation in the RH values with height on 03rd Aug 2017 and the average RH values are around 90%, 45%, 70% and 25% between the surface to 600 hPa, between 600 to 450 hPa, between 450 to 350 hPa and above 350 hPa pressure levels respectively. On 12th July, 2017, cloudburst case; the vertical moisture profile is constant with very high RH values, greater than 88%, up to upper troposphere.

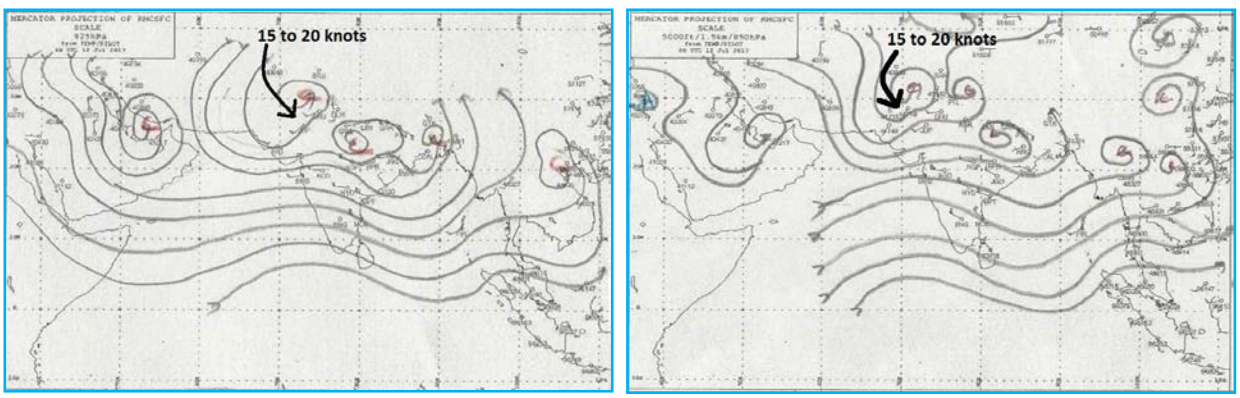
Level of free convection (LFC) is the level at which the temperature of the lifted air parcel becomes equal to that of the surrounding temperature and if lifted further, air parcel would become warmer than its surroundings in a conditionally unstable atmosphere. On T-phi gram, the area between LFC and equilibrium level (EL) gives the CAPE and indicates the vertical extent of the cloud mass. During these cloudburst events, the LFC is at a very low height between 782 to 865 hPa and EL is high in upper troposphere between 115 to 183 hPa pressure levels in four out of five cases as shown in Fig. 6. The large amount of moisture and conditional instability present in the atmosphere during these events as evident from the high PWC and CAPE values resulted into formation of tall convective clouds as visible from the radar images in Fig. 7. The height of clouds are more than 13.6 km over the area where cloudburst occurred on 26th June, 20th July and 3rd August, 2017. The clouds are extended up to 12.1 km and 9 km over the cloudburst region on 12th July and 29th June, 2017 respectively. Of all the cloudburst events, the maximum rainfall intensity of 136 mm/hour is



Figs. 7(i-v). Radar pictures of the cloudburst events on (i) 26th June, 2017 over Dehradun (ii) 29th June, 2017 over Roorkee (iii) 12th July, 2017 over Dehradun (iv) 20th July, 2017 over Jaspur (v) 3rd August, 2017 over Dehradun

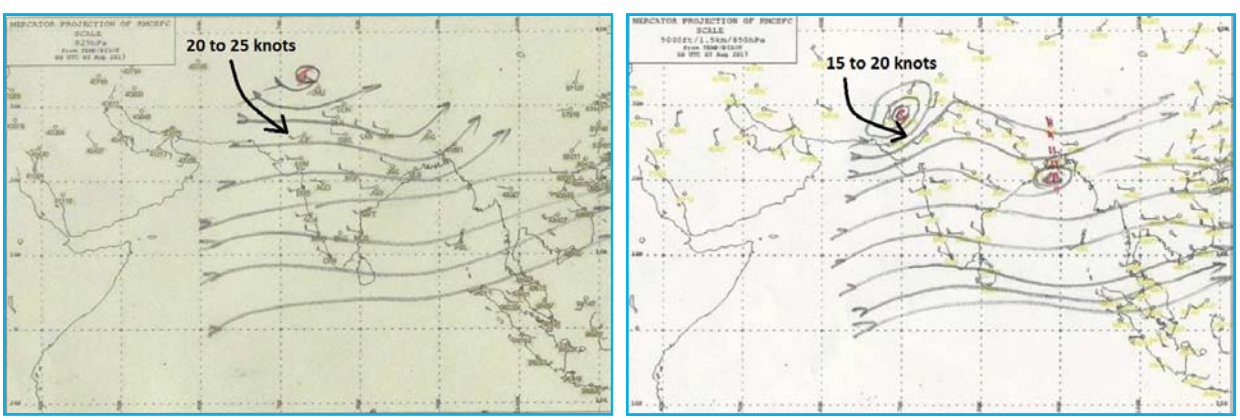


(i) (ii)



925 hPa 850hPa

(iii)



925 hPa 850hPa

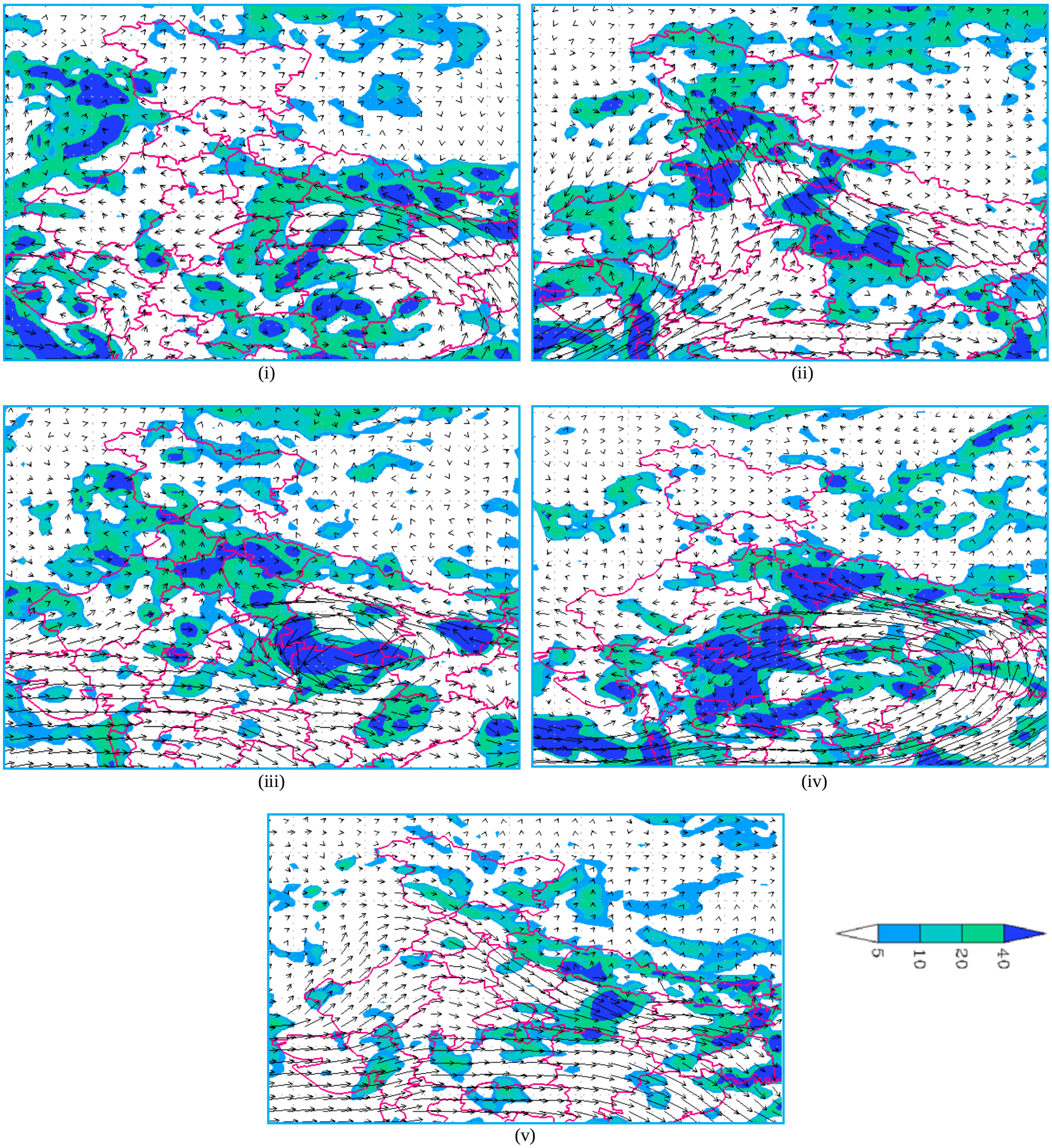
(iv)

Figs.8(i-iv). Upper air chart of (i) 925 hPa level on 25thJune (ii) 925 hPa level on 29thJune (iii) 925 and 850 hPa levels on 12thJuly (iv) 925 and 850 hPa levels on 3rd August

Observed on the 20th July, 2017 event that occurred over Jaspur. On that day, the CAPE and LI are maximum and the distance between EL and LFC is highest as shown in Table 1(i) and Fig. 6.

3.3. *Dynamic conditions during cloud burst events*

According to Grossman & Durran (1984), the interaction of low-level jet with mountains in the Western



Figs. 9(i-v). Moisture flux convergence (1.e05 kg/m^2/s) at (i) 1800 UTC of 25thJune (ii) 0000 UTC of 29th June (iii) 0000 UTC of 11th July (iv) 1800 UTC of 28th July and (v) 1100 UTC of 3rd August

Ghats during monsoon season is responsible for the initiation and persistence of deep convection. Similarly, lower level strong winds and orography of Uttarakhand provide a mechanism to channel a large amount of moisture over smaller areas. The south-easterly wind during monsoon season brings the moisture from Bay of Bengal over the region and the southerly component of wind occasionally strengthened by the south-westerly wind flow from the Arabian Sea across West Rajasthan and Haryana. The moist air mass convergence over the area and blocking of low level strong southerly/south-westerly winds by the northwest to southeast oriented Himalayas facilitates the occurrence of cloudburst events due to deep convection along foothills of Uttarakhand.

Table 1(ii) shows the mean wind direction and speed at lower levels observed over Patiala station during the events mainly from southerly or south-easterly direction and speed between 9 to 22 knots during 4 out of five cloudburst events. Fig. 8 shows the upper air wind charts of 925 and 850 hPa which shows strong south-westerly wind flow from the Arabian Sea in lower levels. The strong south-westerly winds from Arabian sea upto Gujarat Coast starts decelerating downstream towards foothills of western Himalayas providing maximum lifting of moisture along foothills of western Himalayas is essential condition for cloud burst. This can be seen from IMD GFS (12 km) model generated moisture flux convergence product as shown in Fig. 9. Moisture flux convergence is found to be high along foothills of Western Himalayan region during these cloud burst events. On 12th and 20th July cloud burst events moisture flux convergence is more than 40×10^5kg/m^2/s and for all other cases it is between 20 to 40×10^5kg/m^2/s.

3.4. *Temporal analysis*

Temporal analysis showed that two of the events occurred between 0200 to 0300 IST and four out of five cloud bursts events occurred between 0200 to 0900 IST. Also, the cloudburst events that occurred during early morning hours are more intense than the events that occurred during the late morning or in evening hours. Fig. 5 shows the plot between the intensity and the time of occurrence of the cloudburst events. This shows that early morning/morning hours are relatively more favourable for cloudburst events. The large scale favourable synoptic conditions with multiple local instabilities may cause cloud burst events at different places at the same time.

4. Conclusions

(*i*) With the advent of GPRS based AWS, the monitoring of cloudburst events is possible.

(*ii*) The lower level convergence provided by the existence of trough/cyclonic circulations in lower levels and the upper-level divergence provided by movement of western disturbances/trough in westerliesare necessary conditions for the deep vertical development of clouds.

(*iii*) The velocity convergence of strong southwesterly wind flow from the Arabian Sea across West Rajasthan and Haryana is essential for more moisture incursion and rapid orographic lifting of moist air mass over the area due to blocking of moist wind flow by northwest to southeast oriented Western Himalayas and leading to cloud burst events along foothills of Western Himalayan region.

(*iv*) The occurrence of cloudburst event over Uttarakhand is more frequent during the advance and initial phases of the southwest monsoon due to high instability in the atmosphere over the area. The SWEAT index observed in these events is greater than 250.

(*v*) The diurnal temporal pattern of the cloudburst events over Uttarakhand shows that the early morning hours are most conducive for the occurrence due to convective cooling in early morning hours by lowering the dew point depression.

(*vi*) High relative humidity in the lower and upper troposphere and low relative humidity in middle troposphere required for deep convection is observed in these events.

(*vii*) By continuous rainfall monitoring with GPRS based AWS, availability of radar and satellite observations, the nowcasting of cloudburst events at such locations are possible with a lead time of half to an hour. The lead time of nowcast of a cloudburst event can be increased by 1-2 hours with the availability of reflectivity products of WRF, Warning Dissemination & support system - integrated information (WDSS-II) and Advanced Regional Prediction System (ARPS) by incorporating radar data of nearby stations. The favourable synoptic and thermodynamic conditions in association with NWP model outputs can help much more in value addition to nowcast of cloudburst events.

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