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Heavy rainfall forecasting for Dehradun capital city during monsoon season 2020

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सार – देहरादून शहर उत्तराखंड की राजधानी और दून घाटी का हिस्सा है, जो हिमालय और शिवालिक के बीच स्थित है। भारत मौसम विज्ञान विभाग ने मॉनसून ऋतु 2020 से प्रायोगिक आधार पर राजधानी/प्रमुख शहरों के लिए भारी वर्षा की घटनाओं का प्रभाव आधारित पूर्वानुमान (IBF) शुरू किया है। उत्तराखंड के मौसम संबंधी प्रेक्षण और निगरानी नेटवर्क में सुधार और लघु और मध्यम अवधि के संख्यात्मक मौसम पूर्वानुमान (NWP) मॉडल आउटपुट के साथ अच्छी सटीकता के साथ बहुत छोटे स्थानिक पैमाने पर प्रभाव-आधारित पूर्वानुमान प्रदान करना संभव हो गया है। देहरादून शहर के केंद्र के 20 किलोमीटर के दायरे में 5 जनरल पैकेट रेडियो सर्विस (GPRS) आधारित स्वचालित मौसम स्टेशनों (AWS) और 2 स्वचालित वर्षामापी (ARG) के गहन नेटवर्क की मदद से इन घटनाओं का पता लगना और निगरानी करना संभव हो पाया है। इन घटनाओं के स्थानिक विश्लेषण से पता चलता है कि देहरादून शहर में भारी वर्षा में बड़े पैमाने पर सिनॉप्टिक विशेषताओं की जगह स्थानीय भौगोलिक विशेषताओं ने प्रमुख भूमिका निभाई है। राजधानी देहरादून के पूर्वानुमान के लिए हेडके कौशल स्कोर 0.63 और पता लगाने की 100% संभाव्यता पाई गई। अपनी सामान्य स्थिति के उत्तर में मॉनसून द्रोणी की उपस्थिति, हरियाणा या पूर्व-राजस्थान या पश्चिम उत्तर प्रदेश के ऊपर उत्तराखंड के दक्षिण में एक चक्रवाती परिसंचरण तथा 70 डिग्री पूर्व के आसपास एक पश्चिमी विक्षोभ देहरादून शहर में देखा गया। भारी वर्षा की घटना के लिए अनुकूल सिनॉप्टिक सिस्टम पाए गए। पश्चिमी हिमालय की तलहटी में अरब सागर से कभी-कभी तेज दक्षिण-पश्चिमी हवा का प्रवाह भी भारी बारिश के लिए जिम्मेदार पाया जाता है।

ABSTRACT. Dehradun city is Uttarakhand's capital and part of the doon valley, which lies between the Himalayas and the Shivaliks. India Meteorological Department has undertaken the Impact Based Forecasting (IBF) of heavy rainfall events for capital/major cities on an experimental basis from the monsoon season 2020. With the improvement in meteorological observation & monitoring network of Uttarakhand and short & medium range Numerical Weather Prediction (NWP) model outputs, it has become possible to provide impact-based forecast at a very small spatial scale with good accuracy. With the help of a dense network of 5 General Packet Radio Service (GPRS) based Automatic Weather Stations (AWS) & 2 Automatic Rain Gauges (ARG) within a 20 km radius of Dehradun city center, it has become possible to capture & monitor these events. The spatial analysis of these events suggests that the local orographic features rather than large-scale synoptic features played a major role in heavy rainfalls over Dehradun city. The Heidke skill score of 0.63 and 100% probability of detection is found for the capital city forecast of Dehradun. The presence of monsoon trough to the north of its normal position, a cyclonic circulation south of Uttarakhand over Haryana or East-Rajasthan or West Uttar Pradesh and a Western disturbance around 70° E were found to be the synoptic systems favorable for the occurrence of heavy rainfall in Dehradun city. The occasional strong south-westerly wind flow from the Arabian Sea converging over the foothills of the Western Himalayas is also found to be responsible for the heavy downpour.

Key words – Heavy rainfall, Impact-based forecast, Dehradun city forecast, AWS/ARG.

1. Introduction

Dehradun city lies in a valley between the Himalayas and the Shivaliks that are situated in northwest-southeast direction to the north and south of Dehradun, respectively. The 50 years normal annual rainfall of Dehradun city is 2238.3 mm, whereas it receives 1934.2 mm rainfall during four months of monsoon season (CPS, 2014). The annual average number of rainy days in Dehradun city, *i.e.*, the days with 24-hours accumulated rain of 2.5 mm or more, is 85.5, whereas, for monsoon season, it is 64.3. The annual average number of heavy rainfall days lies between

Fig. 1. Network of manned observatories, automatic weather and automatic rain gauge stations in and around Dehradun city

3.8 to 5 in Dehradun and between 3.5 to 4 from June to September (Guhathakurta *et al.*, 2020). Heavy/very heavy rainfalls during the monsoon season makes the settlements in low lying areas and along the rainfed rivers of the city vulnerable to disasters. Therefore, timely and accurate forecasting of heavy rainfalls in and around Dehradun city is essential for disaster management and emergency response authorities in order to mitigate the impact of heavy rainfall in the densely populated areas (Thapliyal, 2021). With the improvement in resolution and frequency of short & medium-range Numerical Weather Prediction (NWP) models output, it has become possible to provide impact-based forecasts at a very small spatial scale with good accuracy.

India Meteorological Department started the Impact Based Forecasting (IBF) of heavy rainfall events for capital/major cities on experimental basis from the monsoon season 2020. The District-level severity based color-coded weather warnings are issued up to 5 days prior to the expected severe weather events. The capital city IBF alert is issued 24 to 48 hours before the occurrence of the event as color-coded bulletins with 12 hourly updates. On the day of occurrence of the event, the warnings are issued at 6 or 3 hourly intervals as required with the expected intensity of rainfall.

The forecasting of severe weather for such a small spatial scale is difficult and the uneven topography of Dehradun further makes it a challenging task. In this study, an attempt is made to analyze the features of heavy rainfall events in Dehradun and identify the favorable synoptic & dynamic conditions responsible for a heavy downpour in the region.

TABLE 1

List of manned and automatic stations in and around Dehradun city

S. No.	Observatory	Type
1.	Mohkampur	Manned
2.	Jollygrant	Manned
3.	Mussoorie	Manned
4.	Dhanolti	Manned
5.	Haripur	Manned
6.	Karanpur	AWS
7.	Jollygrant	AWS
8.	Mussorie	AWS
9.	UCOST	AWS
10.	Sahaspur	AWS
11.	Sahastradhara	ARG
12.	Asharori	ARG

2. Data and methodology

With the improvement in the meteorological observations & monitoring network of Uttarakhand, it has

TABLE 2(a)

2 × 2 Contingency table for the categorical forecasts

		Observed events	
		Yes	No
Forecast event	Yes	a (Hit)	c (False alarm)
	No	b (Miss)	d (Correct non-event)

TABLE 2(b)

List of different skill scores used for the categorical forecasts

S. No.	Skill scores	Formula used	Limits	Remarks
1.	Probability of detection (POD)	a/(a+b)	$0 \leq POD \leq 1$	Higher value signifies good forecast
2.	False alarm rate (FAR)	c/(a+c)	$0 \leq FAR \leq 1$	Lower value signifies good forecast
3.	Critical success index (CSI)	a/(a+b+c)	$0 \leq CSI \leq 1$	Higher value signifies good forecast
4.	True skill statistic (TSS)	(a/a+b) - (c/c+d)	$-1 \leq TSS \leq 1$	Higher value signifies good forecast
5.	Heidke skill score (HSS)	2(ad-bc)/[(a+b) (b+d)+(a+c) (c+d)]	$-1 \leq HSS \leq 1$	Higher value signifies good forecast

become possible to monitor, capture and study in detail the features of heavy rainfall events. In this study, a dense network of 5 manned observatories, 5 GPRS based Automatic Weather Stations (AWS) & 2 Automatic Rain Gauges (ARG) within a radius of 30 km from Dehradun city center is used to capture the heavy rainfall events. This dense network helped in capturing the localized heavy rainfall events, thus providing better verification of forecast. Table 1 shows the details & Fig. 1 shows the network of these manned and automatic stations within Dehradun District's boundary. The three concentric circles are plotted with radii 10 km, 20 km & 30 km.

The 24-hour accumulated rainfall data from these automatic stations and manned observatories in and around Dehradun city is used for the study. The daily all India 0300 UTC surface and 0000 UTC upper air charts are analyzed to find out the favorable synoptic situations associated with the heavy rainfall in Dehradun.

The 2 × 2 contingency table for the categorical forecast verification is shown in Table 2(a). In this, a is the number of correctly forecast events, b is the number of events missed, c is the number of events predicted, but didn't occur and d is the number of correct non-occurrence of non-predicted events. Table 2(b) contains the description of various skill scores derived from these four independent variables. The probability of detection (POD) shows the likelihood that an event can be correctly forecasted without taking incorrect forecasts into account. Therefore, the false alarm rate (FAR) needs to be calculated along with POD to find the forecast's holistic skill score. Critical success index (CSI) is the ratio of hits to the sum of hits, misses and false alarms. According to Schaefer (1990), since CSI does not consider the number of correct non-events (d) and hence is a biased score. True skill statistic (TSS), also known as Hanssen and Kuipers' discriminant (Woodcock, 1976) and Heidke skill score (HSS)(Heidke, 1926), both use all the four independent variables for the calculation. TSS expresses the hit rate relative to the false alarm rate and will remain positive as long as a is greater than c. TSS equal to 0 represents no skill whereas, negative values represent perverse forecasts and can be converted to positive skill simply by replacing all the yes forecasts with no and *vice-versa*. The HSS gives equal weight to hits & correct non-events and false alarms& misses. Doswell *et al.*, 1990 compared the TSS and HSS approaches of forecast verification and found that the TSS approaches the POD in forecasting rare events where the forecasting is dominated by correct forecasts of non-occurrence. Therefore, HSS is superior to the TSS in such situations because it accounts for correct forecasts of null events in a controlled fashion.

Chi-square ($\chi2$) test is utilized to test the statistical significance of heavy rainfall forecast. A 2 × 2 forecast

TABLE 3

Skill scores of the forecast based on 2 × 2 contingency table

Skill score indices	Skill score
Probability of detection	1
False alarm rate	0.5
Missing rate	0
Correct non-occurrence	0.93
Critical success index	0.5
Percentage correct	0.93
True skill score	0.93
Heidke skill score	0.63

TABLE 4

Test for forecast verification of 2 × 2 Contingency Table. Values in brackets are expected frequency

		Observed heavy rainfall		
		Yes	No	Total
Forecasted heavy rainfall	Yes	8(1)	8(19)	16
	No	0(7)	106(99)	106
	Total	8	114	122

$\chi^2_{(\text{computed})} = 49, \quad \chi^2_{(\text{tabulated at } 99.9\%)} = 10.83$

contingency table based on observations and prediction of heavy rainfall is prepared and the chi-square test statistics is calculated as :

$$\chi^2 = \sum \frac{\left(o_{ij} e_{ij}\right)^2}{e_{ij}}$$

where, e_{ij} is expected frequency given by $e_{ij} = \frac{o_i o_j}{n}$, o_i & o_j are marginal column and row frequency respectively, o_{ij} is observed frequency and n is the total sample size. However, for small sample sizes and in cases when the 20% of cells have expected frequencies < 5, we need to use Fisher's exact test because applying the approximation method is inadequate. Therefore, Fisher's exact test is also calculated to determine the non-random associations between the two categorical variables. Fisher (Fisher, 1934) showed that the probability of obtaining any such set of values was given by the hypergeometric distribution:

$$p = \left[\frac{(a+b)!(c+d)!(a+c)!(b+d)!}{a!b!c!d!n!}\right]$$

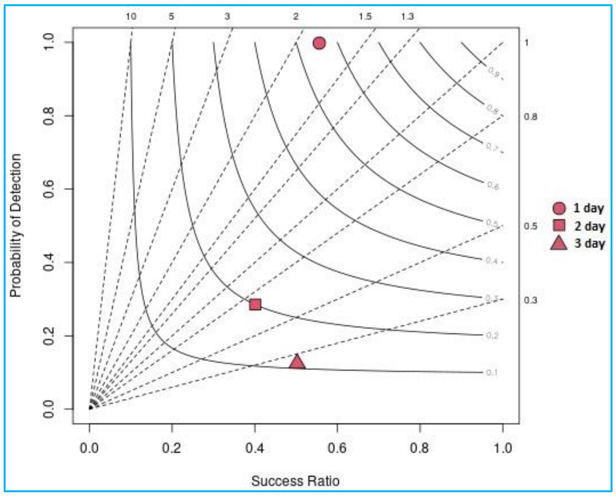


Fig. 2. Categorical performance diagram for all lead times of forecast. Dashed lines depict bias and solid lines depict CSI

TABLE 5

Contingency table with respect to different lead times for the categorical forecast

Lead time	Hit (a)	Miss (b)	False alarm (c)	Correct non-event (d)
1 Day	5	0	4	106
2 Day	2	5	3	110
3 Day	1	7	1	113

Cramér's V (Cramér's, 1946), is used as a post-test to determine the strength of association of these two categorical variables, *i.e.*, observation and prediction of heavy rainfall, after Fisher's exact test has determined the significance. In our case of a 2 × 2 contingency table, Cramér's V is equal to the Phi coefficient. Cramér's V (ϕc) is defined as:

$$\phi_c = \sqrt{\frac{\chi^2 / n}{\min\left(i-1, j-1\right)}}$$

where i & j are the number of columns and rows, respectively. Cramér's V varies from 0, which corresponds to no association between the variables, to 1 representing the complete association.

3. Results and discussion

Out of 122 days of the monsoon period, the impact-based warning was issued on 16 occasions and heavy to very heavy rainfall was observed on 13 numbers of days within 30 km from the Dehradun city and on eight days

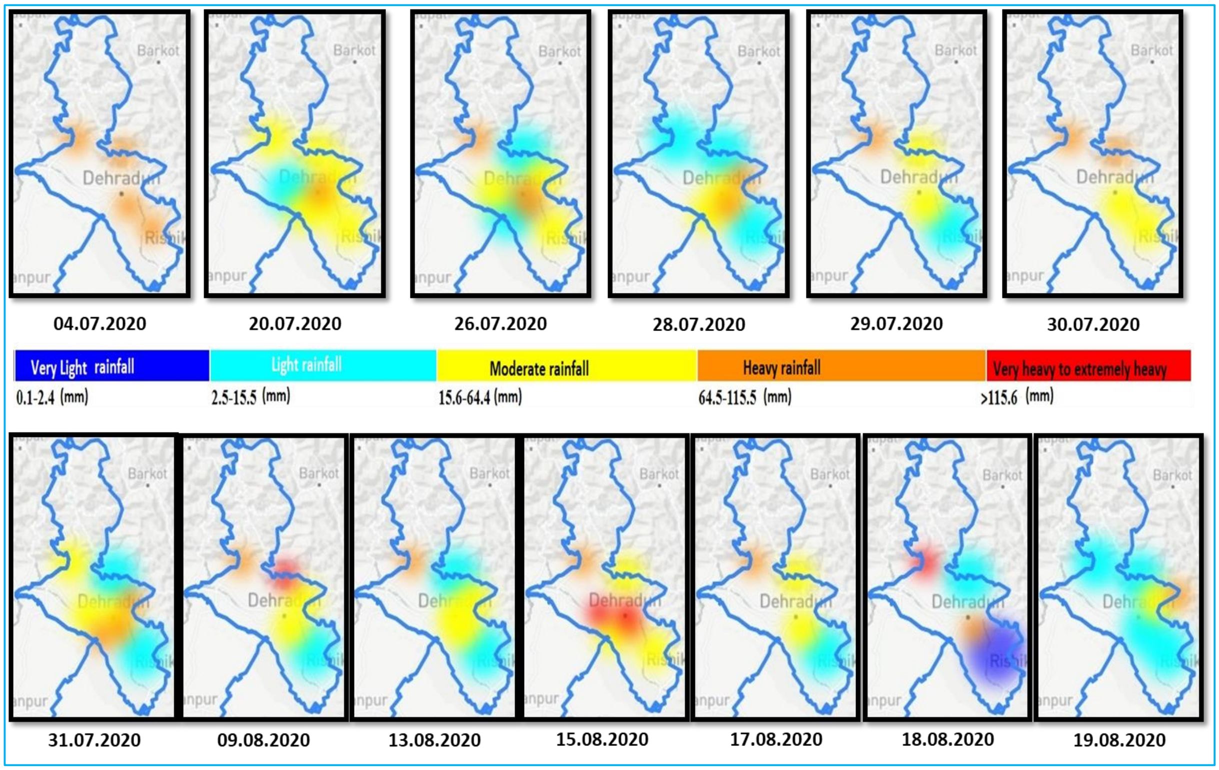


Fig. 3. Intensity based color-coded observed rainfall plot for Dehradun

within 20 km from Dehradun city center. Dehradun is a small city which extends around 8 km in all directions from the city center. However, for this study, the forecast is assumed correct if heavy rainfall was observed within a 20 km radius from the city center.

A 2 × 2 forecast contingency table based on the observations and prediction of heavy rainfall is prepared to calculate the different skill scores of the forecast. As shown in Table 3, the probability of detection is 100%, the false alarm is low and the missing rate is 0. The critical success index, true skill score & Heidke skill scores are0.5, 0.93 & 0.63, respectively. The good values of skill scores don't alone quantify the quality of forecast; therefore, Chi-square (χ^2) test is performed to test the statistical significance of heavy rainfall forecast. As per Table 4, the computed value of the chi-square statistic is 49, which is higher than the tabulated value of chi-square (10.83) with one degree of freedom ata 99.9% significance level. The Fisher's exact test is utilized since the sample size is small with expected frequency less than 5 in one cell. The Fisher exact test statistic value is < 0.00001 and the result is significant at $p < .01$. Hence, the heavy rainfall forecast can be adjudged as significantly skilled. Thereafter, to test the strength of association, Cramér's V (ϕc) is computed, which comes out to be 0.51. Therefore, the high ϕc value suggests that the synoptic & dynamic conditions discussed in this study area strong indicator for heavy rainfall prediction in and around Dehradun.

The lead time of impact based warning ranged from one day to three days for different events. The lead time in case of a false alarm is the duration between the issue of the First Alert and the expected heavy rainfall. Table 5 shows hits, false alarms, correct non-events and misses with respect to different lead times. The hits as well as false alarms of heavy rainfall forecast for Dehradun city decrease with an increase in lead time. The skills scores of different lead time can be concisely displayed using the performance diagram (Roebber, 2009). Fig. 2 shows the performance diagram of the forecast of different lead times. The figure suggests that the performance of the forecast improves greatly as the lead time decreases. The forecasting lead time of a heavy rainfall event for Dehradun city is ≤ 3 days.

3.1. *Spatial scale of heavy rainfall events*

The spatial analysis of heavy rainfall events reveals that the scale of heavy rainfall events is small for most of the occasions. The heavy rainfall is observed within

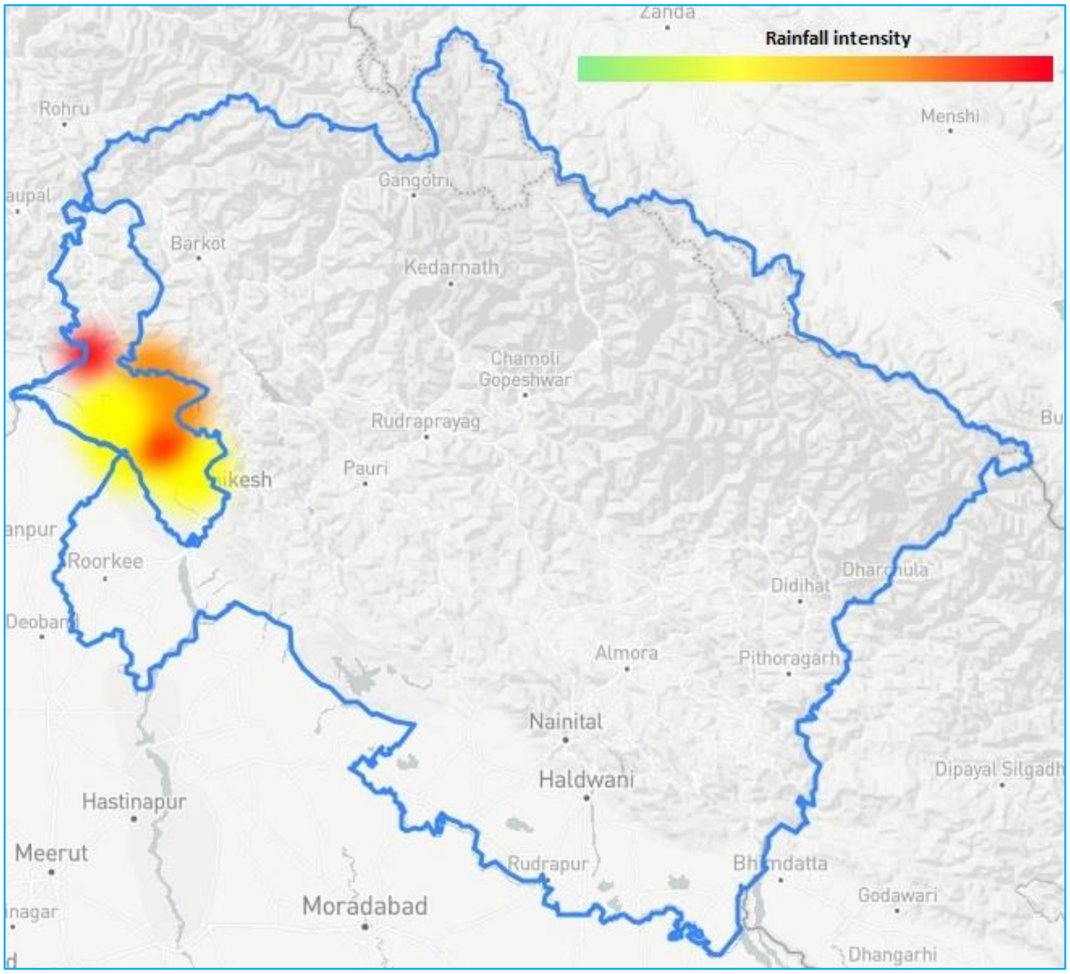


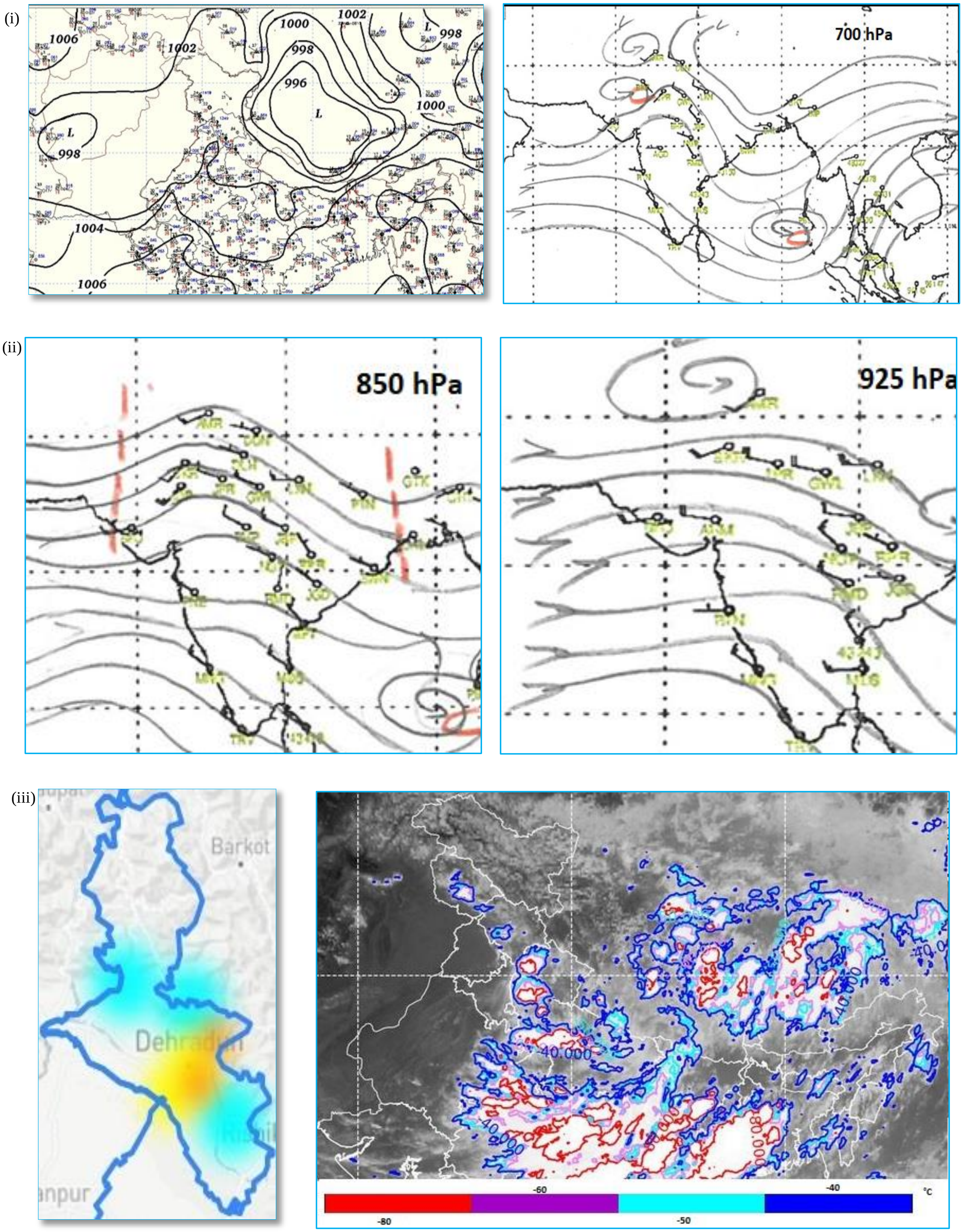
Fig. 4. Total accumulated rainfall of heavy rainfall events during monsoon season 2020 on Uttarakhand map

10 km on five occasions, ~10 km on one occasion, within 20 km on three occasions, ~30 km on two occasions and more than 30 km on two occasions. Fig. 3 shows the district boundary of Dehradun with the distribution of heavy rainfall plotted in and around Dehradun city. It can be seen that the heavy rain occurred in a larger region on 04th & 26th July and 15th & 18th August 2020 and it occurred within a small region of less than 20 km on the remaining days. The stations on the mountain ridge or away from doon valley like Mussoorie, Dhanolti, Jollgrant and Asharori received comparatively lesser rainfall than the stations situated inside the valley. The concentration of intense rainfall in a small region causing considerable variation in the spatial distribution of heavy rainfall may be attributed to the orographic features of the study area. On the days of favourable synoptic conditions, the blocking of moist lower level southerly/southwesterly winds by the surrounding mountains in the north causes more frequent heavy rainfall events in doon valley as compared to the nearby areas.

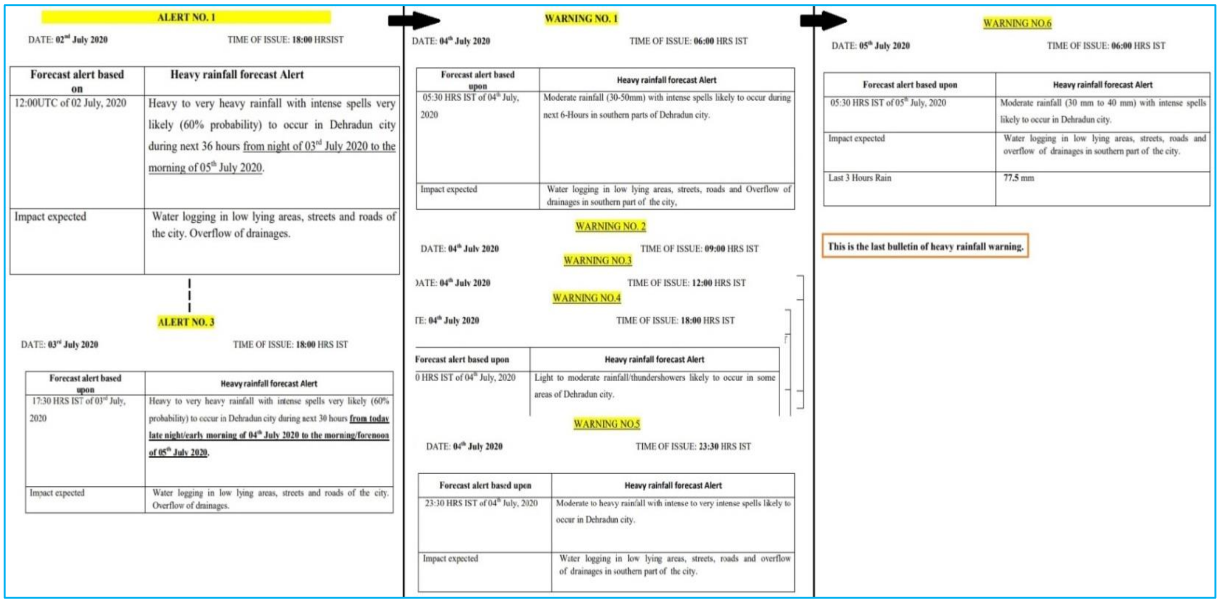
On the occasions when heavy rainfall is experienced on a larger areal extent, the heavy rain is not uniform but has two peaks, one in Dehradun city and the other near 30 km northwest of Dehradun. The peaks can be seen from the accumulated rainfall map in Fig. 4.

3.2. *Synoptic conditions on 28th July, 2020*

On 28th July, 2020, 70 & 69.7 mm rainfall was observed in Sahastradhara and Mohkampur, respectively. Moderate rainfall was observed in Karanpur & Asharori stations, whereas light rainfall was observed on the remaining stations. The scale of the heavy rainfall activity was 10 km. The analysis of all India 0300 UTC surface and 0000 UTC upper air charts indicated the presence of



Figs. 5(i-iii). (i) 0300 UTC analyzed all India surface chart (ii) 0000 UTC analyzed upper air charts for 700 hPa, 850 hPa & 925 hPa levels (iii) Satellite-derived cloud top brightness temperature image on the right and rainfall distribution on the district map of Dehradun on the left



ALERT NO. 1

DATE: **02nd July 2020** TIME OF ISSUE: **18:00** HRSIST

Forecast alert based on	Heavy rainfall forecast Alert
12:00UTC of 02 July, 2020	Heavy to very heavy rainfall with intense spells very likely (60% probability) to occur in Dehradun city during next 36 hours from night of 03rd July 2020 to the morning of 05th July 2020.
Impact expected	Water logging in low lying areas, streets and roads of the city. Overflow of drainages.

ALERT NO. 3

DATE: **03rd July 2020** TIME OF ISSUE: **18:00** HRS IST

Forecast alert based upon	Heavy rainfall forecast Alert
17:30 HRS IST of 03rd July, 2020	Heavy to very heavy rainfall with intense spells very likely (60% probability) to occur in Dehradun city during next 30 hours **from today late night/early morning of 04th July 2020 to the morning/forenoon of 05th July 2020.**
Impact expected	Water logging in low lying areas, streets and roads of the city. Overflow of drainages.

WARNING NO. 1

DATE: **04th July 2020** TIME OF ISSUE: **06:00** HRS IST

Forecast alert based upon	Heavy rainfall forecast Alert
05:30 HRS IST of 04th July, 2020	Moderate rainfall (30-50mm) with intense spells likely to occur during next 6-Hours in southern parts of Dehradun city.
Impact expected	Water logging in low lying areas, streets, roads and Overflow of drainages in southern part of the city,

WARNING NO. 2

DATE: **04th July 2020** TIME OF ISSUE: **09:00** HRS IST

WARNING NO.3

ATE: **04th July 2020** TIME OF ISSUE: **12:00** HRS IST

WARNING NO.4

TE: **04th July 2020** TIME OF ISSUE: **18:00** HRS IST

Forecast alert based upon	Heavy rainfall forecast Alert
0 HRS IST of 04th July, 2020	Light to moderate rainfall/thundershowers likely to occur in some areas of Dehradun city.

WARNING NO.5

DATE: **04th July 2020** TIME OF ISSUE: **23:30** HRS IST

Forecast alert based upon	Heavy rainfall forecast Alert
23:30 HRS IST of 04th July, 2020	Moderate to heavy rainfall with intense to very intense spells likely to occur in Dehradun city.
Impact expected	Water logging in low lying areas, streets, roads and overflow of drainages in southern part of the city.

WARNING NO.6

DATE: **05th July 2020** TIME OF ISSUE: **06:00** HRS IST

Forecast alert based upon	Heavy rainfall forecast Alert
05:30 HRS IST of 05th July, 2020	Moderate rainfall (30 mm to 40 mm) with intense spells likely to occur in Dehradun city.
Impact expected	Water logging in low lying areas, streets, roads and overflow of drainages in southern part of the city.
Last 3 Hours Rain	77.5 mm

This is the last bulletin of heavy rainfall warning.

Fig. 6. Image of alert from 1 to 3 (left section), warning bulletins from 1 to 5 (centre section) and de-warning bulletin (right section) for heavy rainfall event in Dehradun city issued from 2nd to 5th July, 2020

monsoon trough close to the foothills of the Himalayas on 27th & 28th July. A cyclonic circulation laid over southwest Rajasthan between 2.1 km & 3.1 km above mean sea level on 28th July. A Western Disturbance as a cyclonic circulation laid over north Pakistan & neighborhood and extended upto 2.1 km above mean sea level on 27th July and became less marked on 28th July. However, a trough in westerlies extended from Jammu Division to the Northeast Arabian Sea off Pakistan coast at 1.5 km above mean sea level on 28th July, 2020. Strong south-westerly wind flow of the order of 20 to 25 kts at 850 hPa & 925 hPa levels from the Arabian Sea converging over foothills of the western Himalayan region was present on 28th July. This causes large moisture incursion and convergence near foothills and is responsible for intense rainfall activities. The satellite-derived cloud top brightness temperature image [Fig. 5(iii)] shows the vertical growth of the clouds up to150 hPa pressure level over Dehradun. The 0300 UTC surface and 0000 UTC upper air analyzed charts are shown in Figs. 5(i&ii).

The synoptic and dynamic conditions discussed above were observed on most of the days of heavy rainfall events over Dehradun. The favorable synoptic and dynamic conditions and the blocking of moisture by the steep mountains in the north of Dehradun cause heavy rainfall during the monsoon season. The mean sea level pressure, upper-level winds & accumulated rainfall products from regional and global NWP models suggested the probable formation of such synoptic situations up to 5 days in advance with reasonably good accuracy.

3.3. *Alert & warning bulletins issued for heavy rainfall event on 4th July*

Fig. 6 shows the two Alerts, five warning bulletins and one de-warning bulletin issued for the 4th July heavy rainfall event in Dehradun city. Based on the synoptic analysis and NWP model guidance, the first alert was issued on 2nd July, *i.e.*, three days before the expected severe weather in Dehradun city. The alert included the expected intensity of rainfall, probability of occurrence, duration of the spell, affected location and the impact. The regular alerts were issued every 12 hours and the last alert was issued on the evening of 03rd July 2020. After that, regular warning bulletins containing observed rainfall, expected quantitative precipitation, specific area to be affected (less than 10 km) and impact for the next 3 to 6 hours were issued at 3 or 6 hourly intervals from the morning of 4th July till the cessation of the event. The surface observations from manned and automatic stations, the latest satellite & radar pictures and NWP model guidance were used to issue these short-range warnings. A de-warning bulletin informing the cessation of the intense activity was issued on the morning of 5th July, 2020.

During the monsoon season 2020, the above procedure of disseminating location-specific impact-based warnings was followed on all the occasions of heavy rainfall events in Dehradun. The alert issued 3 to 5 days prior to the expected severe weather event is useful for disaster managers in terms of planning for deployment of necessary resources in the vulnerable areas. The 3/6 hourly warning bulletins are useful in disaster mitigation and recovery. It informs the disaster managers about the severely affected areas, their improvement/ deterioration probability and new areas expected to be affected.

4. Future scope

Installation of three new x-band Doppler weather radars in Uttarakhand will help provide location-specific nowcast (0.5 to 3 hours) for severe weather, a better estimation of rainfall with detection of heavy rains and generation of warnings. The radar wind & reflectivity product output will provide additional inputs to the NWP models for generating better weather forecasts. The reflectivity product of the IMD WRF model can be improved for very-short range forecasting. At present, the WRF model cannot pick up the observed reflectivity over the region and the forecast reflectivity product is also not good and useful. Doppler weather radar can provide area-specific rainfall and storm warnings which is beneficial for aviation related services, disaster management and emergency response authorities.

5. Conclusions

(*i*) The spatial scale of these heavy rainfall events is found to be very small on most occasions and is of the order of less than 10 km. This suggests that the local orographic features rather than large-scale synoptic features played a significant role in heavy rainfall events in Dehradun city.

(*ii*) Out of 122 days of the monsoon period, the impact-based warning was issued on 16 occasions and the severe weather was observed on eight numbers of days in Dehradun city with a 100% probability of detection. The critical success index, true skill score & Heidke skill scores were found to be 0.5, 0.93 & 0.63, respectively. Fisher's exact test showed that the forecasting skills were statistically significant at a 99.9% significance level. The analysis of the skill of forecasts issued at different lead times suggests that the hits as well as the false alarms of heavy rainfall forecast for Dehradun city decrease with an increase in lead time. A significant improvement in forecast performance is observed as the lead time decreases.

(*iii*) The presence of monsoon trough to the north of its normal position, a cyclonic circulation south of Uttarakhand over Haryana or East-Rajasthan or west Uttar Pradesh and a Western disturbance around 70°E were found to be the synoptic systems favorable for the occurrence of heavy rainfall in Dehradun city.

(*iv*) The occasional strong south-westerly wind flow upto mid-tropospheric levels from the Arabian Sea converging over foothills of the western Himalayan region in association with the above synoptic conditions is responsible for dumping moistures in the foothills and resulting in a heavy downpour.

(*v*) The analysis of these favorable synoptic and dynamic conditions, along with the NWP model guidance, can help in the forecasting of such severe weather events at small spatial scale up to3 to 5 days lead time with fairly good accuracy.

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