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Verification of heavy rainfall warning over Bihar and Uttar Pradesh

M. MOHAPATRA, H. R. HATWAR and S. R. KALSI

India Meteorological Department, New Delhi, India

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e mail : mohapatra_imd@yahoo.com

सार – भारत मौसम विज्ञान विभाग मौसम वैज्ञानिक उपखंड़ों के लिए भारी वर्षा की चेतावनी तब जारी करता है जब उस उपखंड में स्थित किसी भी वर्षा मापी केन्द्र में अपेक्षित 24 घंटों में 64.5 मि. मी. अथवा इससे अधिक वर्षा के होने की संभावना होती है। यद्यपि ये चेतावनियाँ काफी पहले से दी जाती रहीं हैं और अब छोटे स्थानिक पैमाने पर भी जारी की जा रही है किंतु फिर भी इन चेतावनियों के मात्रात्मक मूल्यांकन के लिए बहुत कम प्रयास किए गए हैं। अतः मानसून ऋतु के जुलाई–अगस्त के प्रमुख महीनों के दौरान पूर्वी उत्तर प्रदेश, पश्चिमी उत्तर प्रदेश और बिहार के समरूप मौसम वैज्ञानकि उपखंडों को भारी वर्षा के होने की दी जाने वाली चेतावनी को सही सिद्ध करने के लिए अध्ययन आरंभ किया गया है। इस कार्य के लिए हाल ही के पिछले पांच वर्षों (2001–2005) के आँकड़ों और 1970 के पूर्वार्द्ध के पाँच वर्ष – काल के आँकड़ों पर विचार किया गया है। इस संबंध में जब उपखंड के कम से कम दो केन्द्रों में भारी वर्षा वाले दिन रिकार्ड किए गए वह दिन उस उपखंड में भारी वर्षा वाले दिन के रूप में माना गया।

इस अध्ययन में की की गई जाँच से हाल ही के पिछले पाँच वर्षों में बिहार में 64 प्रतिशत, पूर्वी उत्तर प्रदेश में 52 प्रतिशत और पश्चिमी उत्तर प्रदेश में 53 प्रतिशत भारी वर्षा के होने की संभावना का पता चलता है। 1970 के पूर्वार्द्ध की अपेक्षा 2001–2005 के दौरान के पूर्वानुमान के कौशल में थोड़ा सुधार आया है। पूर्वानुमान करने की संभावना में 10–20 प्रतिशत बढ़ोतरी हुई इसके साथ ही अप्रर्याप्त आँकडों की दर तथा भ्रामक आँकडों की दर में कमी आई है। फिर भी भ्रामक आँकडों की दर सामान्य से अधिक की ओर संकेत कर रही है। वर्ष 2001–2005 की अवधि के दौरान घटित हुई भारी वर्षा की घटनाओं से जुडी हुई सिनाप्टिक स्थितियों को एकत्र किया गया और उनका विश्लेषण किया गया है। अप्रत्याशित रूप से होने वाली भारी वर्षा की घटनाओं के विश्लेषण से यह पता चलता है कि यधपि सिनाप्टिक चार्टों और एन. डब्ल्यू. पी. आउटपुट की समुचित व्याख्या चेतावनी देने में सुधार कर सकती है तो भी वर्तमान समय में उपलब्ध पूर्वानुमान प्रणाली भारी वर्षा की प्रत्येक घटना का पहले से ही पुर्वानुमान देने में अभी भी सक्षम नहीं है।

ABSTRACT. India Meteorological Department (IMD) issues heavy rainfall warning for a meteorological sub-division when the expected 24 hours rainfall over any rain gauge station in that sub-division is likely to be 64.5 mm or more. Though these warnings have been provided since long and are also now being issued for smaller spatial scales, very few attempts have been made for quantitative evaluation of these warnings. Hence, a study is undertaken to verify the heavy rainfall warning over the representative meteorological sub-divisions of east Uttar Pradesh (UP), west UP and Bihar during main monsoon months of July and August. For this purpose data of the recent 5 years (2001-2005) and also for another epoch of 5 years in the early 1970s has been taken into consideration. In this connection, the day when heavy rainfall is recorded over atleast two stations in a sub-division, has been considered as a heavy rainfall day for that sub-division.

This study of verification shows that probability of detection of heavy rainfall is 64% over Bihar, 52% over east UP and 53% over west UP for the recent 5 years. Compared to early 1970s, there has been slight improvement in the forecast skill during 2001-2005 with probability of detection increasing by about 10-20% and with decrease in missing rate and false alarm rate. However, the false alarm rates are still large indicating higher bias towards over-prediction. The synoptic conditions associated with the heavy rainfall events have been collected for the period 2001-05 and analysed. The analysis of the unanticipated heavy rainfall events suggests that though proper interpretation of synoptic charts and NWP outputs could improve the warnings, the forecast system available even today is still not capable to capture every heavy rain event in advance.

Key words – Heavy rainfall, Monsoon, Forecast verification.

1. Introduction

As per the criteria of India Meteorological Department (IMD), the heavy rainfall is said to have occurred over a station, if the accumulated rainfall during past 24 hrs as recorded at 0830 hrs IST is 64.5 mm or more. Accordingly, IMD issues heavy rainfall warning for a meteorological sub-division when the expected 24 hours rainfall over any raingauge station in that sub-division is likely to be 64.5 mm or more. Though these warnings have been provided since the inception of IMD and are also now being issued for smaller spatial scales, a few attempts have been made for quantitative evaluation of these warnings. The verification of heavy rainfall warning is essential to monitor their value and quality. It also helps to compare the quality of different forecast systems and to find out the better one. The verification is mostly performed by calculating the forecast accuracy and its variation/improvement over the time. According to Murphy (1993), the goodness of forecast is distinguished by consistency (degree to which the forecast corresponds to the forecaster's best judgement about the situation), value (the degree to which the forecast helps a decision maker to realize some incremental economic and other benefits) and quality (degree to which the forecast corresponds to what actually happened). Murphy (1993) has described nine aspects (attributes) that contribute to the quality of a forecast. These include bias, resolution, accuracy, skill, discrimination and uncertainty etc. There are many types of forecast each of which calls for slightly different methods of verification (Thornes and Stephenson, 2001 and Jolliffe & Stephenson, 2003). These include deterministic forecast (occurrence/non-occurrence of an event like heavy rainfall), probabilistic forecast (*e.g.*, probability of precipitation and ensemble forecast) and qualitative forecast (like 5 day outlook). In this study, the heavy rainfall warnings issued by IMD New Delhi for three meteorological sub-divisions, *viz*., Bihar, east Uttar Pradesh (UP) and west UP (Fig. 1) during the main monsoon months of July and August have been verified for two different 5 years epochs of 1971-1975 and 2001-2005. The objective of choosing these two 5 years epochs is to assess the impact of numerical weather prediction (NWP) models guidance on heavy rainfall warning. The methodology of verification and data used in this regard are described in details in Sec.2.

Bihar and most parts of UP lie to the north of the normal position of the monsoon trough in July and August (Srinivasan *et al*., 1972 and Pathan, 1993). The northern most parts of these states are sub-mountainous. The monsoon rainfall over these states mainly depends on the activity of the monsoon trough. The common synoptic situations that produce good rainfall in Bihar and UP include low pressure systems and upper air cyclonic

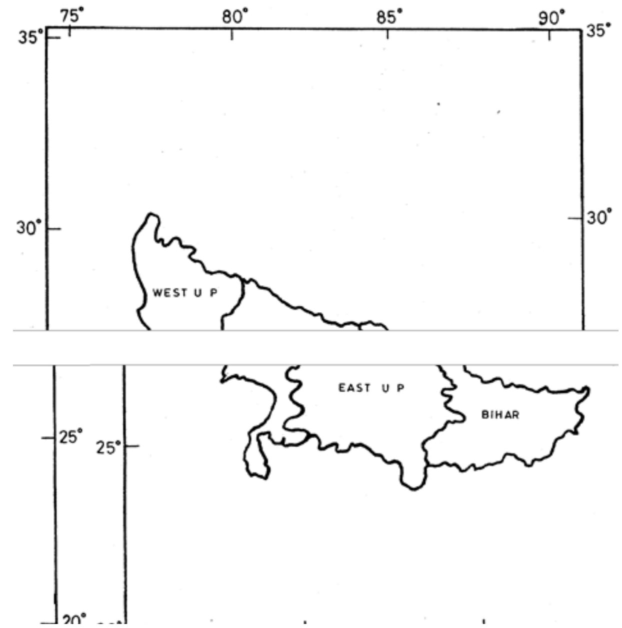


Fig.1. Region of study under consideration

circulations over the region and neighbourhood, monsoon trough across the region, north-south oriented trough in the monsoon westerlies or a westerly trough moving across the western Himalayas or Tibet in the upper troposphere (Srinivasan *et al*., 1972). In association with the above synoptic situations, UP and Bihar experience floods due to heavy rainfall during the main monsoon months of July and August. Rainfall, even of the order of 30-40 cm in 24 hours has occurred in UP, the amount being as high as 50 cm in south east UP, while the amount of the order of 40-50 cm has also been reported in Bihar (Srinivasan *et al*., 1972). Synoptic meteorologists have always given very high credence to the synoptic conditions while issuing these warnings. The synoptic situations associated with the heavy rainfall events during the recent 5 years have been analysed in Sec.3 along with the results of verification.

2. Data and methodology

For the recent 5 years (2001-2005), the heavy rainfall warnings valid for next 24 hours as issued by Northern Hemispheric Analysis Centre (NHAC), IMD, Mausam Bhavan, New Delhi in respect of west UP, east UP and Bihar during main monsoon months of July and August have been verified. For this purpose, the daily rainfall as recorded at different raingauge stations in these sub-divisions under the district-wise rainfall monitoring scheme (DRMS) have been taken into consideration. The days of occurrence of heavy rainfall events, when atleast two rain gauge stations in a meteorological sub-division

TABLE 1

Average number of heavy rainfall days over the meteorological sub-divisions under consideration during July-August

Meteorological sub-division	Average number of heavy rainfall days
Bihar	12.4
East UP	12.8
West UP	3.4

report heavy rainfall have been found out. The data have been quality checked by comparing heavy rainfall with rainfall over the surrounding stations. The days of forecast issued by NHAC, IMD, New Delhi for occurrence of heavy rainfall for each of the three meteorological sub-divisions under consideration have been collected from the special daily weather reports (SDWR) published by NHAC.

For the period of 1971-1975, the heavy rainfall warnings issued by the office of Deputy Director General of Meteorology (Weather Forecasting), IMD, Pune have been considered, as weather forecasting at NHAC was non-existent at that time. The data on days of occurrence of heavy rainfall and heavy rainfall warning have been collected from India daily weather reports published by IMD, Pune. The heavy rainfall warnings during 1971-1975 and 2001-2005 have been analysed and results of verification have been compared keeping the above limitations in mind.

The various forecast verification methods are described in Stanski *et al.*, (1989) and Wilks (1995). Heavy rainfall occurrence is a dichotomous and deterministic variable. Accordingly, the suitable verification methods have been used in the study using a 2 × 2 contingency table (Wilks, 1995) as given below.

Observed	*Forecast*	
	Yes	*No*
Yes	A	B
No	C	D

Using this contingency table the following indices have been calculated.

Probability of detection (POD) = A/(A+B),

False alarm rate (FAR) = C/(C+A)

Missing rate (MR) = B/ (B+A),

Correct non-occurrence (C-NON)=D/(C+D)

Critical success index (CSI) = Threat score = A/(A+B+C)

Bias for occurrence (BIAS) = (A+C)/(A+B)

Percentage correct (PC) = (A+D)/(A+B+C+D)*100 = Hit rate*100

Heidke skill score (HSS) = $2(AD-BC)/[(B^2+C^2+2AD+(B+C)(A+D)]$

For a perfect forecast, POD = 1, FAR = 0, MR = 0, CSI = 1, BIAS = 1, PC = 100% and HSS = 1.

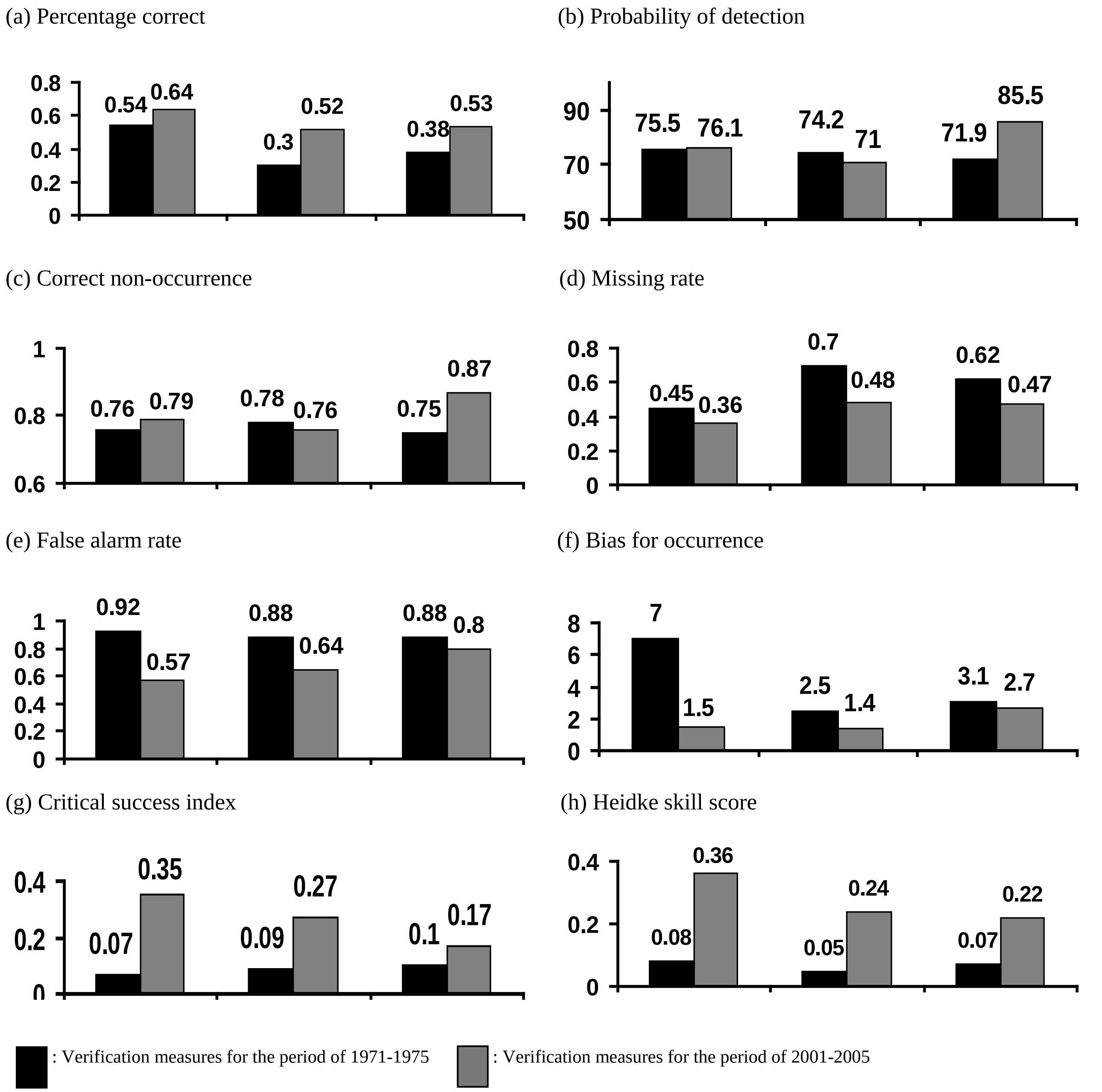
3. Results and discussion

The results of verification of heavy rainfall warning are presented and discussed in sec.3.1. The causative synoptic systems for heavy rainfall over different meteorological sub-divisions under consideration are analysed and discussed in sec.3.2. The unanticipated heavy rainfall events are presented and discussed in sec.3.3.

3.1. *Verification of heavy rainfall warning*

The frequency of heavy rainfall events for the two 5 year epochs along with the annual average over these 10 years is given in Table 1. The heavy rainfall was more frequent in the recent epoch in east UP and Bihar where as the opposite occurred over west UP in the early 1970s. The year 1972 was a phenomenal drought in which pronounced deficiencies in rainfall occurred in July and August (Sikka, 1980) even over these areas that usually receive good rainfall during break monsoon conditions. Though each of both the epochs had two droughts, their character was quite different. The average annual frequency of heavy rainfall days during this 10 years period is turning out to be somewhat higher because of the presence of 4 drought years.

The results of verification of heavy rainfall warning for these sub-divisions are presented in Figs. 2(a-h). The probability of detection of heavy rainfall events over Bihar has improved by only 10 % where as the improvement in UP is roughly of the order of 15-20%. But it is still higher at 64% compared to east and west UP where it stands now at about 52%. Similarly, the missing rate has decreased all over though the improvement is higher in UP. Since the heavy rainfall events can cause



Figs. 2(a-h). Verification measures of heavy rainfall warning over Bihar, east UP and west UP during July-August based on data of 1971-1975 and 2001-2005. (a) Percentage correct, (b) probability of detection, (c) correct non-occurrence, (d) missing rate, (e) false alarm rate, (f) bias for occurrence, (g) critical success index and (h) Heidke skill score

flood, they have high cost on being missed. The false alarm rate has considerably gone down in Bihar and continues to be high over west UP where improvement is very little. Considering both the heavy and non-heavy rainfall events, the percentage of correct forecast is now maximum over west UP (85.5%) followed by Bihar and east UP. The higher percentage of correct forecast is mainly due to higher percentage of correct forecast of non-heavy rainfall events. The forecast of non-occurrence of heavy rainfall over a meteorological sub-division has the high quality but little value. The present methodology, which is mostly based on synoptic methods and interpretation of numerical weather prediction models guidance is still very subjective. Hence, the warnings issued are highly biased to over-forecasting and cause frequent false alarms. The BIAS indicates that over-forecasting has considerably gone down in Bihar and is now maximum for west UP. However, the deliberate over-

TABLE 2

Synoptic systems associated with heavy rainfall over at least two stations in Bihar

S. No.	Synoptic systems	Number of heavy rainfall days (%)
1.	Monsoon trough lying close to the foothills of the Himalayas with/without north-south oriented trough in westerlies in lower levels across east UP/ Bihar	16 (25.8)
2.	Monsoon trough extending eastwards to Assam across Bihar with north-south oriented trough in westerlies at lower levels over east UP/ Bihar	03 (4.8)
3.	Monsoon trough extending eastwards to Assam across Bihar with embedded LPSC over different regions (*i-iv*)	09 (14.5)
	(*i*) LPSC over east UP	04
	(*ii*) LPSC over Bihar	02
	(*iii*) LPSC over Sub-Himalayan West Bengal and Sikkim	01
	(*iv*) LPSC over Assam and Meghalaya	02
4.	Western end of monsoon trough lying close to the foothills of the Himalayas and eastern end extending from Bihar to north Bay of Bengal	13 (21)
5.	Western end of monsoon trough lying close to the foothills of the Himalayas and eastern end extending from Bihar to north Bay of Bengal with LPSC over the north Bay and adjoining areas	05 (8.1)
6.	Monsoon trough lying to the south of Bihar and extending eastwards to Bangladesh with an embedded cyclonic circulation over Bangladesh	01 (1.6)
7.	Monsoon trough lying to the south of Bihar or passing through extreme southern part of Bihar and extending to north Bay of Bengal alongwith embedded LPSC over different regions (*i-vi*)	15 (24.2)
	(*i*) LPSC over Jharkhand	04
	(*ii*) LPSC over Chhattisgarh	02
	(*iii*) LPSC over Gangetic West Bengal	02
	(*iv*) LPSC over north Bay	02
	(*v*) LPSC over Orissa	01
	(*vi*) LPSC over Haryana/west UP/ Uttaranchal	04
	Total	62 (100)

forecasting of an event like heavy rainfall may be justified, even though it may lead to a large number of false alarms, as the heavy rainfall events which can cause flood have high cost on being missed.

The critical success index that determines the threat score has considerably improved in Bihar from 0.07 to 0.35. It is now 0.27 over east UP and 0.17 over west UP. The Heidke skill score is also included in the Fig. 2. The improvements in the various indices are mainly attributed to the improved analysis and forecast products through numerical weather prediction models guidance available to the forecasters in recent years. However, consistent effort should be made to reduce false alarm and missing rates and hence to increase the probability of detection of heavy rainfall events. This is possible only either by improving the quality of the NWP models or by statistical interpretation of the NWP outputs by objective linking of forecast with realised rainfall.

Verifying the skill of ECMWF forecasts based on T213L31 model, Petroliagis *et al*. (1997) have shown that probabilistic precipitation predictions are less skillful for predicting extreme weather events, possibly due to poor Ensemble Prediction System (EPS) model resolution. Roy Bhowmik *et al*., (2007) have documented the current level of skill of the operational NWP model of IMD based on daily 24 hrs forecast run of the model during the two normal monsoon years 2001 and 2003. Their study shows that the accuracy in prediction of location and magnitude of rainfall fluctuates considerably. The study suggests to maximize data ingest and to use better data assimilation scheme in the model to improve the forecast skill. The poor representation of local topography and other features necessitates statistical interpretation of NWP products. Maini *et al*. (2002) have verified the direct model output obtained from NWP models and the statistical interpretation forecast obtained by Perfect Prognostic Method (PPM) based on ECMWF analysis. Their study

TABLE 3

Synoptic systems associated with heavy rainfall over at least two stations in east UP

S. No.	Synoptic systems	Number of heavy rainfall days (%)
1.	Monsoon trough lying close to the foothills of the Himalayas with/without north-south oriented trough in westerlies in lower levels across east UP	08 (12.5)
2.	Monsoon trough extending eastwards to Assam with embedded cyclonic circulation/north-south oriented trough in westerlies at lower levels over east UP	08 (12.5)
3.	Monsoon trough extending eastwards to Assam with embedded LPSC over Bihar	08 (12.5)
4.	Monsoon trough extending through east UP to north Bay of Bengal	02 (3.1)
5.	Monsoon trough extending through west UP, east UP to north Bay of Bengal with embedded LPSC over different regions (*i-vii*)	36 (56.3)
	(*i*) LPSC over west UP/ Haryana	06
	(*ii*) LPSC over east UP	08
	(*iii*) LPSC over Jharkhand	08
	(*iv*) LPSC over Chhattisgarh	03
	(*v*) LPSC over Gangetic West Bengal	04
	(*vi*) LPSC over Orissa	04
	(*vii*) LPSC over north Bay of Bengal	03
6.	Monsoon trough lying to the south of east UP and extending to the Bay of Bengal with embedded LPSC over northeast Madhya Pradesh/ Chhattisgarh	02 (3.1)
	Total	64 (100)

shows that the statistical interpretation forecast has good skill and is an improvement over direct model output.

3.2. *Synoptic systems associated with heavy rainfall events*

Information in respect of the synoptic systems associated with heavy rainfall events has been gathered only for the recent 5 year epoch. These synoptic systems witnessed over Bihar, east UP and west UP are analysed and discussed in Sec.3.2.1, 3.2.2 and 3.2.3 respectively.

3.2.1. *Synoptic systems associated with heavy rainfall over Bihar*

The synoptic systems associated with heavy rainfall events over Bihar during July-August are shown in Table 2. The heavy rainfall events are dominantly associated with the (*i*) monsoon trough lying close to the foothills of the Himalayas with/without north-south oriented trough in westerlies in lower levels across east UP/Bihar, (*ii*) monsoon trough extending eastwards to Assam across Bihar with embedded cyclonic circulation/ north-south oriented trough in westerlies at lower levels over east UP/Bihar/sub-Himalayan West Bengal and Sikkim, (*iii*) western end of monsoon trough lying close to the foothills of the Himalayas and eastern end extending from Bihar to north Bay of Bengal with/without low pressure systems (LPS)/cyclonic circulations over Bihar/ north Bay of Bengal and (*iv*) monsoon trough lying to the south of Bihar or passing through extreme southern part of Bihar and extending to the north Bay of Bengal along with embedded LPS over Jharkhand. More than 90% of the heavy rainfall events in Bihar are associated with the above mentioned synoptic systems. When the monsoon trough shifts to the north close to the Himalayas and westerlies prevail over north India, north-south oriented trough/circulations form in the westerlies and move from west to east causing rain over UP and Bihar. In some cases, the land lows also develop over these regions causing intense rainfall (Srinivasan *et al*., 1972). The heavy rainfall can also occur in isolated cases with LPS/

TABLE 4

Synoptic systems associated with heavy rainfall over at least two stations in west UP

S. No.	Synoptic systems	Number of heavy rainfall days (%)
1.	Western end of the monsoon trough lying close to the foothills of the Himalayas or across west UP and eastern end either lying close to the foothills or extending to Assam	04 (23.5)
2.	Western end of the monsoon trough lying across west UP and eastern end extending to north Bay with embedded LPSC over different regions (*i*-*v*)	11 (64.7)
	(*i*) LPSC over west UP	03
	(*ii*) LPSC over east UP	03
	(*iii*) LPSC over Jharkhand	03
	(*iv*) LPSC over northwest Bay of Bengal	01
	(*v*) LPSC over Haryana	01
3.	Western end of monsoon trough lying to the south of west UP, eastern end extending to the north Bay of Bengal with embedded LPSC over different regions (*i*-*ii*)	02 (11.8)
	(*i*) LPSC over west Madhya Pradesh	01
	(*ii*) LPSC over Orissa	01
	Total	17 (100)

cyclonic circulation (LPSC) over Haryana/west UP/ Uttaranchal, north Bay/Gangetic West Bengal and Orissa if the associated monsoon trough passes through Bihar.

3.2.2. *Synoptic systems associated with heavy rainfall over east UP*

The synoptic systems associated with heavy rainfall events over east UP during July-August are shown in Table 3. The heavy rainfall events are dominantly associated with the (*i*) monsoon trough lying close to the foothills of the Himalayas with/without north-south oriented trough in westerlies in lower levels across east UP/Bihar, (*ii*) monsoon trough extending eastwards to Assam across east UP and Bihar with embedded cyclonic circulation/north-south oriented trough in westerlies at lower levels over east UP/ Bihar and (*iii*) monsoon trough passing through east UP and extending to north Bay of Bengal along with embedded LPSC over east UP/ Jharkhand/Chhattisgarh. More than 70% of the heavy rainfall events in east UP are associated with the above mentioned synoptic systems. The heavy rainfall can also occur on some occasions over east UP when the monsoon trough passes through east UP to north Bay with embedded LPSC over north Bay, Orissa and Gangetic West Bengal. The heavy rainfall over UP and Bihar may also be attributed to the rapid northwestward movement of this embedded system. On some of the occasions there has been interaction with the extratropical westerlies with the embedded LPSC over the north Bay of Bengal. Srinivasan *et al.*, (1972) have also shown that in common with northwest India, Uttar Pradesh and Bihar are also affected by disturbances in middle latitude westerlies. These westerlies interact even with the LPSC located far away over the north Bay of Bengal. On rare occasions the heavy rainfall occurs over east UP when the monsoon trough passes to the south of the east UP, but embedded with LPSC over northeast Madhya Pradesh/Chhattisgarh. With reference to heavy rainfall to the north of the monsoon trough at the sea level earlier studies (Srinivasan *et al*., 1972) have shown that there are occasions when the axis of the monsoon trough slopes northward with height causing more rainfall to the north of the surface location of the monsoon trough.

3.2.3. *Synoptic systems associated with heavy rainfall over west UP*

The synoptic systems associated with heavy rainfall events over west UP during July-August are shown in Table 4. The heavy rainfall events over west UP are dominantly associated with the (*i*) Western end of the monsoon trough lying close to the foothills of the Himalayas or across west UP and eastern end either lying close to the foothills or extending to Assam and (*ii*) Western end of the monsoon trough lying across west UP and eastern end extending to north Bay with embedded LPSC over Haryana, west UP, east UP and Jharkhand. More than 82% of the heavy rainfall events in west UP are associated with the above mentioned synoptic

TABLE 5

Synoptic systems associated with unanticipated heavy rainfall events in Bihar

S. No.	Synoptic systems	Number of heavy rainfall days
1.	(*i*) Monsoon trough lying close to the foothills of the Himalayas	04
	(*ii*) Monsoon trough lying close to the foothills of the Himalayas with low level cyclonic circulation over the north Bay	01
2.	(*i*) Monsoon trough extending eastwards to Assam across Bihar	01
	(*ii*) Monsoon trough extending eastwards to Assam across Bihar with embedded cyclonic circulation at lower levels over Assam and Meghalaya	02
3.	(*i*) Western end of the monsoon trough lying close to the foothills of the Himalayas and eastern end extending from east UP/Bihar to north Bay	02
	(*ii*) Western end of the monsoon trough lying close to the foothills of the Himalayas and eastern end extending from Bihar to north Bay with low level cyclonic circulation over Bihar	02
4.	(*i*) Monsoon trough passing through west UP, east UP, south Bihar and north Bay with cyclonic circulation over west UP	01
	(*ii*) Monsoon trough passing through west UP, east UP, south Bihar and north Bay with cyclonic circulation over east UP	03
5.	(*i*) Monsoon trough passing through west UP to north Bay and lying south of Bihar with low over north Bay and cyclonic circulation over north Pakistan and adjoining Jammu and Kashmir extending upto 3.1 km above sea level	03
	(*ii*) Monsoon trough passing through west UP to north Bay and lying south of Bihar with low/ cyclonic circulation over Jharkhand	02
	Total	21

systems. On rare occasions, the heavy rainfall occurs over west UP when the monsoon trough passes to the south of the east UP extending to north Bay, but embedded with LPSC over west Madhya Pradesh. The heavy rainfall can also occur on a few occasions over west UP when the monsoon trough passes through west UP to north Bay with embedded LPSC over Orissa/north Bay of Bengal, especially when there is interaction from the extra-tropical systems with the monsoon circulation.

3.3. *Unanticipated heavy rainfall events*

The synoptic systems associated with the heavy rainfall events, which could not be anticipated and hence not predicted by NHAC, IMD, New Delhi are analysed for Bihar, east UP and west UP. The heavy rainfall over Bihar mainly due to (*i*) low level circulations over Bihar/east UP, (*ii*) monsoon trough lying over the south Bihar with embedded systems over north Bay interacting with systems in mid-latitude westerlies, (*iii*) monsoon trough passing through west UP to north Bay and lying to the south of Bihar with low/cyclonic circulation over Jharkhand, (*iv*) monsoon trough extending eastwards to Assam across Bihar with embedded cyclonic circulation at lower levels over Assam and Meghalaya, (*v*) western end of the monsoon trough lying close to the foothills of the Himalayas and eastern end extending from east UP/Bihar to north Bay, (*vi*) monsoon trough lying close to the foothills of the Himalayas and (*vii*) monsoon trough lying close to the foothills of the Himalayas with cyclonic circulation developing over the north Bay could not be anticipated in advance (Table 5). Most of these are the textbook conditions for heavy rainfall occurrence. Question arises whether their influence was underestimated. This may not be so because similar looking patterns often do not give rise to similar outcomes. This may also be supported by the fact that in cases that amounted to over forecasting, similar patterns are also observed (not shown). It is also apparent that there are some processes producing heavy rainfall that could not be visualized by the forecaster even through the use of the NWP products guidance.

According to Srinivasan *et al.*, (1972), during the monsoon season, air over UP and Bihar is very warm and humid with a fairly high degree of latent instability. As a result convective type of clouds and precipitation are common. Mishra *et al*. (1988) have shown the intense rainfall that developed over UP and Bihar in association with a convective cloud cluster. Though the mesoscale models are supposed to simulate these developments, it actually does not happen so. The case of recent Mumbai storm of 26 July, 2005 is a pointer in this regard. The prediction of the timing, location, organization and structure of the mesoscale cloud system, especially over tropics is recognized as one of the biggest challenges in mesoscale modeling. None of the operational models could figure out the huge rainfall that paralysed the

TABLE 6

Synoptic systems associated with unanticipated heavy rainfall events in east UP

S. No.	Synoptic systems	Number of heavy rainfall days
1.	Monsoon trough lying close to the foothills of the Himalayas	02
2.	(*i*) Monsoon trough extending eastwards to Assam across east UP	01
	(*ii*) Monsoon trough extending eastwards to Assam through east UP with embedded low/cyclonic circulation over Bihar	04
3.	Monsoon trough extending through east UP to north Bay of Bengal	02
4.	Monsoon trough extending through east UP to north Bay of Bengal with embedded LPSC over different regions (*i*-*v*)	15
	(*i*) lower level cyclonic circulation over west UP/ Haryana	02
	(*ii*) Lower level cyclonic circulation over east UP	06
	(*iii*) Low/upper air cyclonic circulation over Jharkhand	04
	(*iv*) Low over Orissa	01
	(*v*) Low over north Bay of Bengal and extra tropical system affecting northwest India	02
5.	Monsoon trough lying to the south of east UP and extending to the Bay of Bengal with embedded LPSC over northeast Madhya Pradesh/Chhattisgarh	03
	Total	27

lifeline infrastructure for days together in that metropolis (Jenamani *et al*., 2006). Bohra *et al.*, (2006) have also outlined the inadequacy of the numerical guidance available on that day. Of course, when the satellite radiance data was assimilated in the global model run at UKMO, using appropriate data assimilation technique, the results improved further.

Like Bihar, the heavy rainfall over east UP due to low level cyclonic circulation over the region or neighbourhood also could not be anticipated (Table 6). In addition, the heavy rainfall due to the monsoon trough lying to the south of UP with embedded system over Chhattisgarh/north Madhya Pradesh could not be anticipated, though it is possible with northward sloping of the monsoon trough in some cases. The interaction of mid-latitude westerlies with the monsoon flow, which can cause good rainfall (Srinivasan *et al*., 1972), could not be used to predict heavy rainfall. Similar is the case as in case of east UP with the unanticipated heavy rainfall events over west UP (not shown).

In all the three sub-divisions, it appears that large percentage of cases of unanticipated cases are those in which sudden changeover from the dry regime to wet regime is occurring. This is also not getting figured out properly in the numerical models. A high resolution numerical model with good physics and dynamics that uses the modern sophisticated 4DVAR data assimilation technique should be able to resolve this interaction well.

The above results and discussion suggest that though proper weightage to the small scale systems like low level cyclonic circulation over the region and neighbourhood, the interaction of mid-latitude westerlies with the monsoon systems, the northward sloping of the monsoon trough embedded with LPSC to the immediate south of the region can help in improving the warning skill, it is eventually the numerical models that have to be improved further to improve the scope of warnings. The statistical interpretation of the numerical weather prediction models guidance linking the location/grid specific precipitation forecast from suitable models with the actual precipitation can reduce the subjectivity and hence improve the accuracy of heavy rainfall warning.

4. Conclusions

The following broad conclusions are drawn from the above results and discussion.

(*i*) The probability of detection of heavy rainfall has increased to 64% over Bihar, 52% over east UP and 53% over west UP during 2001-2005. There is substantial increase in the critical success index, which is now 0.35 over Bihar, 0.27 over east UP and 0.17 over west UP. The Heidke skill score is 0.36 over Bihar, 0.24 over east UP and 0.22 over west UP. There has been slight improvement in the forecast skill with probability of detection increasing by about 10-20% and decrease in missing rate and false alarm rate compared to that during

1971-1975. However, the false alarm rates are still large indicating higher bias towards over-prediction. The slight improvement in recent years is mainly due to the numerical weather prediction models guidance available to the forecasters.

(*ii*) The analysis of the synoptic systems associated with heavy rainfall events, especially the unanticipated events suggests that proper weightage to (*i*) the small scale systems like low level cyclonic circulation over the region and neighbourhood, (*ii*) the interaction of mid-latitude westerlies with the monsoon systems and (*iii*) the northward sloping of the monsoon trough embedded with LPSC to the immediate south of the region alongwith the use of advanced NWP models can immensely help in improving the warning skill. In addition, the poor performance may be due to the subjectivity involved in the present method of heavy rainfall warning, which largely depends on the expertise/ability of decision making of the forecaster. The interpretation of the numerical weather prediction models guidance by suitable linking of the location/grid specific precipitation forecast from the suitable model(s) with the actual precipitation can reduce the subjectivity and hence improve the accuracy of heavy rainfall warning.

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