

## Evaluation of heavy rainfall warning over India during summer monsoon season

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*(Received 6 February 2008, Modified 28 July 2009)*

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**सार** – भारत मौसम विज्ञान विभाग (आई.एम.डी.) मौसम वैज्ञानिक उपखंड के लिए भारी वर्षा की चेतावनी तब जारी करता है जब उपखंड के किसी भी वर्षा मापी स्टेशन में संभावित 24 घंटों की वर्षा 64.5 मि.मी. अथवा इससे अधिक होने की संभावना होती है। हालाँकि ये चेतावनियाँ भारत मौसम विज्ञान विभाग के आरंभ होने की तारीख से उपलब्ध कराई जाती रही हैं फिर भी इन चेतावनियों मात्रात्मक मूल्यांकन के लिए कुछेक प्रयास किए गए हैं। अतः इस शोध-पत्र में मानसून ऋतु के महीनों (जून - सितंबर) और समूची ऋतुओं के दौरान भारत के 36 मौसम वैज्ञानिक उपखंडों में भारी वर्षा की चेतावनियों को सही सिद्ध करने के लिए अध्ययन किया गया है। इस प्रयोजन के लिए हाल ही के पिछले पाँच वर्षों (2002-2006) के आँकड़ों पर विचार किया गया है। इस संबंध में, जब उपखंड के कम से कम एक स्टेशन में भारी वर्षा वाले दिन रिकार्ड किए गए वह दिन उस उपखंड में भारी वर्षा वाले दिन के रूप में माना गया।

ग्रीष्मकालीन मानसून ऋतु के दौरान भारत में भारी वर्षा की चेतावनियों की कौशल की श्रेणियों में अत्यधिक स्थानिक और कालिक भिन्नताएँ होती हैं। समूचे मानसून ऋतु को देखते हुए लक्ष्यद्वीप, दक्षिण पूर्वी प्रायद्वीप, विदर्भ, मराठवाड़ा, जम्मू और कश्मीर, अरुणाचल प्रदेश और नागालैंड, मणिपुर, मिजोरम और त्रिपुरा (एन.एम.एम.टी.) जैसे कम आवृत्ति वाले भारी वर्षा के क्षेत्रों में हाइडके कौशल श्रेणी (एच.एस.एस.) अपेक्षाकृत कम (<0.20) होती है। कोंकण और गोवा, मध्य प्रदेश और गुजरात क्षेत्र में यह अधिक (>0.50) होती है। पूर्वानुमानकत्ताओं के लिए उपलब्ध सांख्यिकीय मौसम पूर्वानुमान (एन.डब्ल्यू.पी.) निदर्श के मार्गदर्शन के कारण कई वर्षों से विवेचनात्मक सफल सूचकांक और हाइडके कौशल श्रेणी में क्रमिक वृद्धि से पूर्वानुमान के कौशल में सुधार आया है। तथापि दक्षिण पश्चिमी भारत, दक्षिण पूर्वी प्रायद्वीप और एन.एम.एम.टी. के कई उपखंडों में अपर्याप्त आँकड़ों की दर और भ्रामक आँकड़ों की दर अभी तक बहुत अधिक (>0.50) 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 the inception of IMD, a few attempts have been made for quantitative evaluation of these warnings. Hence, a study is undertaken to verify the heavy rainfall warnings over 36 meteorological sub-divisions of India during monsoon months (June-September) and season as a whole. For this purpose, data of recent 5 years (2002-2006) has been taken into consideration. In this connection, the day when heavy rainfall is recorded over at least one station in a sub-division, has been considered as a heavy rainfall day for that sub-division.

There is a large spatial and temporal variability in skill scores of heavy rainfall warnings over India during summer monsoon season. Considering the monsoon season as a whole, the Heidke Skill Score (HSS) is relatively less (<0.20) over the regions with less frequent heavy rainfall like Lakshadweep, southeast peninsula, Vidarbha, Marathwada, Jammu & Kashmir, Arunachal Pradesh and Nagaland, Manipur, Mizoram & Tripura (NMMT). It is higher (> 0.50) over Konkan & Goa, Madhya Maharashtra and Gujarat region. There has been improvement in the forecast skill with gradual increase in the critical success index and Heidke skill score over the years mainly due to the Numerical Weather Prediction (NWP) models' guidance available to the forecasters. However, the false alarm rate and missing rate are still very high (> 0.50), especially over many sub-divisions of northwest India, southeast peninsula and NMMT.

**Key words** – Heavy rainfall, Monsoon, Forecast verification.

### 1. Introduction

There is large spatial and temporal variability in the occurrence and intensity of heavy rainfall over India

during monsoon season (Rakhecha and Pisharoty, 1996). Dhar and Nandargi (1993 & 1993a) have found that severe rainstorms over different parts of India do not occur uniformly. According to them, during the period

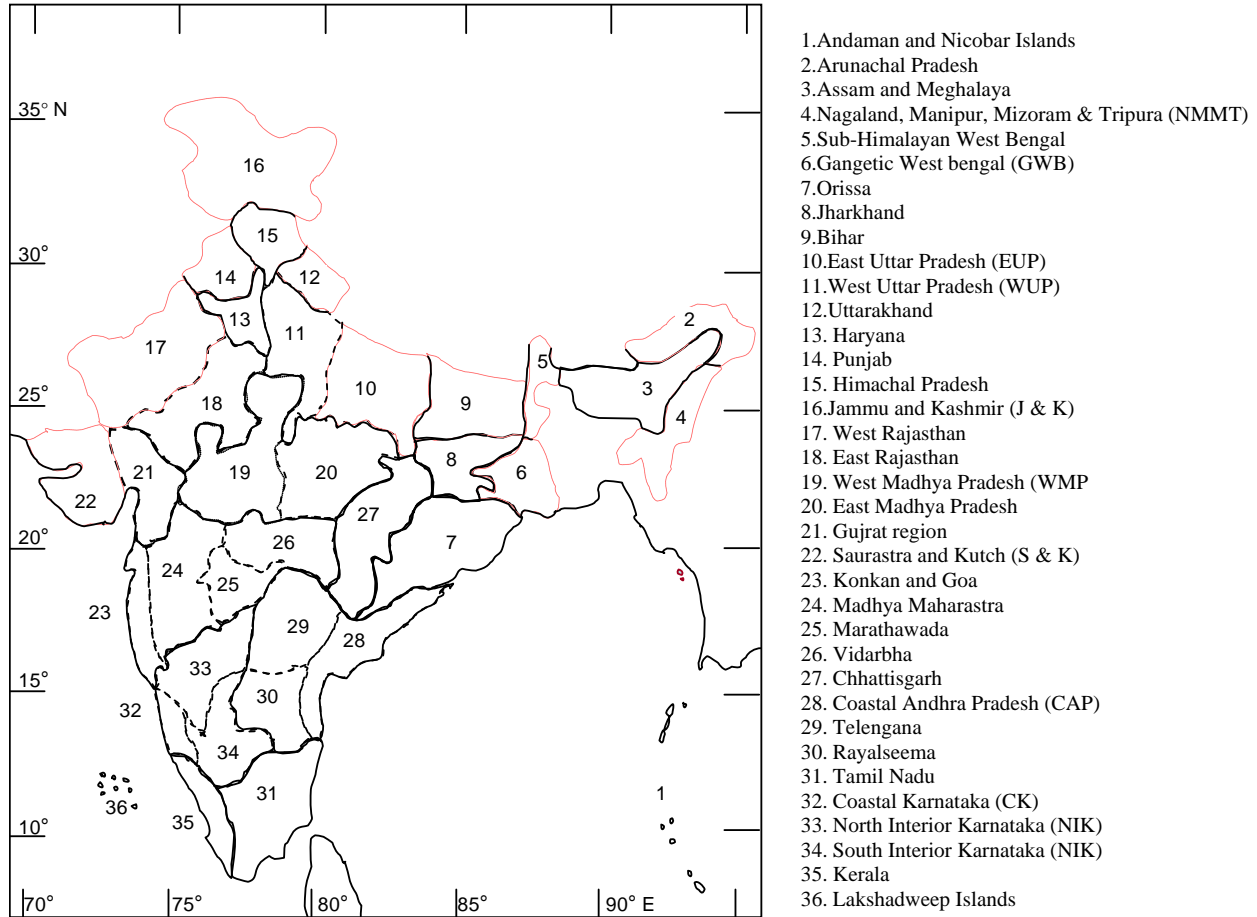


Fig. 1. Meteorological sub-divisions of India

from 1880 to 1990, 97 rainstorms have occurred over the country. The number of rain storms has been maximum over undivided Madhya Pradesh (15) followed by Maharashtra (12), Gujarat and Karnataka (9 each) and Orissa (8). Also the break up of meteorological disturbances causing the rainstorms indicates that most of the rainstorms are caused due to Low Pressure Systems (LPS). Dhar and Nandargi (1993) found that the boundaries of zones of occurrence of rain storms broadly tally with the orographic boundaries of mountain ranges in the respective region indicating significant role played by orography in heavy rainfall distribution and intensity. Apart from the LPS, the off-shore trough/vortex near the west coast and mid-tropospheric cyclones also cause heavy rainfall over the west coast, Madhya Maharashtra and Gujarat region. Similarly, the northward shifting of the monsoon trough towards the foothills of the Himalayas causes the heavy rainfall along the foothills of the Himalayas (Rao, 1976). All these studies indicate that interaction of basic monsoon flow with the synoptic systems and orography due to the Western Ghats, Eastern Ghats, other hill peaks and above all, the Himalayas leads

to spatial variation in occurrence and intensity of heavy rainfall.

The heavy rainfall events lead sometimes to flood conditions and hence need to be predicted well in advance. India Meteorological Department (IMD) has been issuing heavy rainfall warning on a regular basis as and when it is expected. As per criteria of 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 rain gauge station in that sub-division is likely to be 64.5 mm or more. However, a few attempts have been made for quantitative evaluation of these warnings. The verification of heavy rainfall warning is essential to monitor its value and quality. It also helps to compare the quality of different forecast systems and to find out the better one. According to Murphy (1993), the goodness of forecast is distinguished by consistency, value and quality. 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.

Considering all the above, the heavy rainfall warnings issued by IMD, New Delhi for 36 meteorological subdivisions (Fig. 1) during the monsoon months and season as a whole have been verified for 5 year period (2002-2006). The objective of choosing the recent 5 year period is to assess the impact of numerical weather prediction (NWP) models' guidance on heavy rainfall warning. The forecast of occurrence/non-occurrence of an event like heavy rainfall is a deterministic forecast (Thornes and Stephenson, 2001 and Jolliffe and Stephenson, 2003). Accordingly, the appropriate method has been applied in this study to verify the heavy rainfall warning. The detailed methodology of verification and data used in this regard is described in Sec. 2.

**2. Data and methodology**

For the recent 5 years (2002-2006), 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 36 meteorological sub-divisions of India during monsoon months and season as a whole have been verified. For this purpose, the daily rainfall as recorded at different rain gauge 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 at least one rain gauge station in a meteorological sub-division reports 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 meteorological sub-divisions under consideration have been collected from the Special Daily Weather Reports (SDWR) published by NHAC.

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) = 1 - POD

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<sup>2</sup> + C<sup>2</sup> + 2AD + (B+C) (A+D))]

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

C-NON = 1 and HSS = 1.

The quantitative evaluation of heavy rainfall warning based on rainfall observation from one station as a representative of meteorological sub-division may not be justified at some occasions. Though the warnings are issued at meteorological sub-division scale, some of the sub-divisions are exceptionally larger in size for such studies. These are some of the limitations of the present study.

**3. Results and discussion**

The mean patterns of heavy rainfall events during different monsoon months and season as a whole are presented and analysed in Sec.3.1. The various verification scores including POD, MR, FAR, BIAS, C-NON, PC, CSI and HSS of heavy rainfall warnings are analysed and discussed in Sec.3.2-3.8. The verification scores for India as a whole considering all the meteorological sub-divisions together are presented and discussed in Sec.3.9. The major implications of the study are also presented at the end of the Sec.3.

*3.1. Average number of days of heavy rainfall*

The average number of days of heavy rainfall events over different meteorological sub-divisions during different summer monsoon months and season as a whole are shown in Figs. 2(a-e). The number of heavy rainfall days is higher over orographically dominant regions like west coast including Gujarat region, Madhya Maharashtra and Assam & Meghalaya during main monsoon months of July and August as well as season as a whole. It endorses the earlier findings of Srinivasan *et al.*, (1972), Dhar and Nandargi (1993, 1993a) and Rakecha and Pisharoty

**Figs. 2(a-e).** Average number of heavy rainfall days during (a-e) summer monsoon months and season as a whole

(1996) that orography plays a dominant role on the occurrence of heavy rainfall.

Higher number of heavy rainfall days over Orissa during July, August and season as a whole may be due to

the fact that the heavy rainfall over Orissa mainly occurs due to the LPS over northwest Bay of Bengal (Mohapatra and Mohanty, 2005) and the LPS mostly develops over northwest Bay of Bengal during July, August and season as a whole (Mohapatra and Mohanty, 2004).

**Figs. 3(a-e).** Probability of detection (POD) of heavy rainfall over India during (a-e) summer monsoon months and season as a whole

The number of heavy rainfall days is less over southeast peninsula during July, August and season as a whole. It may be due to the fact that it lies on the lee side of the Western Ghat with basic southwesterly monsoon

flow being anticyclonic over the region. However, the southeast peninsula gets more frequent heavy rainfall during June and September. The heavy rainfall occurs in association with thunderstorm activity due to north-

**Figs. 4(a-e).** Missing rate (MR) of heavy rainfall events over India during (a-e) summer monsoon months and season as a whole

south oriented trough/wind discontinuity in lower tropospheric levels in June. During September, the LPS sometimes forms in the lower latitude and move across south peninsula causing heavy rainfall over southeastern parts. The number of days of heavy rainfall is also less

over northwest India covering west Rajasthan, Punjab, Haryana and Jammu & Kashmir (J&K) during July, August and season as a whole as these regions are rarely affected by westward moving LPS developing over the Bay of Bengal (Jadhav, 2002 and Sikka, 2006).

**Figs. 5(a-e).** False alarm rates (FAR) of heavy rainfall events over India during (a-e) summer monsoon months and season as a whole

### 3.2. Probability of detection (POD) and missing rate (MR)

There is large scale spatial and temporal variability of POD over India Figs. 3(a-e). It is higher over the region with more frequent heavy rainfall events and *vice versa*. It

is higher along the west coast including Gujarat region and Madhya Maharashtra during different monsoon months and season as a whole. It is higher over Assam and Meghalaya and Sub-Himalayan West Bengal and Sikkim only during June and July, the months of higher rainfall (Srinivasan *et al.*, 1972). The POD is relatively

**Figs. 6(a-e).** Bias for occurrence (BIAS) of heavy rainfall events over India during (a-e) summer monsoon months and season as a whole

higher over central India extending from Orissa to Gujarat region, as it lies to the south of the normal position of the monsoon trough and to the south of the usual track of movement of LPS developing over the north Bay of Bengal (Pathan, 1993; Jadhav, 2002 and Sikka, 2006). The southwest sector of the westward moving LPS gets

more heavy rainfall due to maximum low level convergence and upward vertical motion (Rajamani and Rao, 1981). All the above results indicate that the heavy rainfall due to interaction of basic monsoon flow with the orography and the heavy rainfall due to the LPS could be predicted more successfully.



The heavy rainfall over the less prone regions like southeast peninsula and northwest India went undetected more frequently. It may be stated that the heavy rainfall generally occurs over southeast peninsula and northwest India in association with cyclonic circulations/trough during all India weak monsoon conditions and interaction of mid-latitude westerly systems with monsoon flow respectively.

The MR is mirror image of the POD as discussed in data and methodology section. Hence, the MR is less over the heavy rainfall prone region and more over the region with less frequent heavy rainfall [Figs. 4(a-e)].

### 3.3. False alarm rate (FAR)

The FAR is less than 25% over heavy rainfall prone regions of Madhya Maharashtra, Gujarat region and east Rajasthan during the season as a whole [Figs. 5(a-e)]. Considering individual months, it is less (<25%) over heavy rainfall prone regions of Madhya Maharashtra in June, August and September, Gujarat region during July and August and east Rajasthan in August and September. It is also less than 25% over the less prone region of Saurashtra and Kutch in August and September. It may be due to the fact that the occurrence of heavy rainfall over these regions are more systematic and mainly occur in association with well defined synoptic systems like west coast trough, mid-tropospheric cyclones and westward moving low pressure systems developing over the Bay of Bengal. The FAR is also relatively less over east central India, especially Orissa during all the months and the season as a whole. It may be due to the fact that heavy rainfall warnings are mainly issued for this region when it is likely to be affected by the LPS.

The FAR is more than 75% over J&K, NMMT and parts of interior peninsula covering Vidarbha, Marathwada, north interior Karnataka and Rayalaseema which are also less prone for heavy rainfall as seen from Figs. 2(a-e). The FAR over these regions can be reduced by objective evaluation of interaction of basic monsoon flow with the orography and synoptic scale systems. It is only possible with statistical and dynamical downscaling of NWP model products.

### 3.4. Bias for occurrence (BIAS)

The BIAS greater than 1 is considered as over-warning and smaller than 1 is considered as under-warning. However, considering an arbitrary threshold of BIAS > 1.2 as over-warning, there is over-warning over central parts covering Jharkhand, Chhattisgarh, Madhya Pradesh, Vidarbha, Marathwada and coastal Andhra Pradesh during the season [Figs. 6(a-e)]. As the LPS over the north Bay of Bengal show large variability in its

movement across land (Mohapatra and Mohanty, 2005), there is large uncertainty in the occurrence of heavy rainfall over these sub-divisions of the country. As a result, the over-warning of heavy rainfall in association with the LPS increases over these sub-divisions. Also, there is over-warning over orographically dominant regions like Konkan & Goa, coastal Karnataka, Arunachal Pradesh and NMMT. The over-warning over Arunachal Pradesh and NMMT may be due to the fact that warnings are very often issued over whole northeastern region without discrimination based on orographic interaction with basic monsoon flow, though heavy rainfall occurs more frequently over Assam & Meghalaya than over Arunachal Pradesh and NMMT [Figs. 2(a-e)]. The over-warning over coastal Karnataka and Konkan & Goa may be attributed to the fact that the warnings are more biased towards the climatology of heavy rainfall events over these regions. As the present methodology which is mostly based on synoptic methods and interpretation of NWP models guidance is still very subjective, the warnings issued are highly biased to over-forecasting and cause frequent false alarms. However, the deliberate over-forecasting of an event like heavy rainfall over a flood prone region may be justified, even though it may lead to a large number of false alarms as the heavy rainfall events over such flood prone regions have high cost on being missed.

There is under-warning (with BIAS < 0.8) over the region with less heavy rainfall like southeast peninsula, west Rajasthan, Punjab and Haryana during individual monsoon months and season as a whole [Figs. 6(a-e)]. It may be attributed to the fact that the interaction of mid-latitude westerly systems with the monsoon flow leading to heavy rainfall events could not be well simulated by the NWP models. There is also under-warning over heavy rainfall regions like Gujarat, east Rajasthan, Madhya Maharashtra, Uttar Pradesh (UP), Bihar and Gangetic West Bengal during most of the months and season as a whole. The analysis of synoptic systems suggests that the heavy rainfall over Uttar Pradesh and Bihar which lie to the north of the normal location of the monsoon trough can occur even due to small scale systems like low level cyclonic circulation. These heavy rainfall events could not be detected either by NWP model products or synoptic tools leading to under-warning. The under-warning over Madhya Maharashtra, Gujarat region and east Rajasthan may be reduced by giving proper weightage to the west coast trough, mid-tropospheric cyclones and other small scale synoptic and sub-synoptic systems and suitable downscaling of NWP model products.

### 3.5. Correct non-occurrence (C-NON)

The forecast of non-occurrence of heavy rainfall over a meteorological sub-division has high quality but

**Figs. 7(a-e).** Correct non-occurrence (C-NON) of heavy rainfall events over India during (a-e) summer monsoon months and season as a whole

little value. However, the results indicate that the C-NON is higher over the region with less heavy rainfall and *vice versa* [Figs. 7(a-e)]. It is less (< 70%) over the west coast, northeastern states, Sub-Himalayan West Bengal &

Sikkim, Lakshadweep and Andaman & Nicobar Islands during June, west coast, Orissa, Sub-Himalayan West Bengal & Sikkim and northeastern states in July, Orissa, Chhattisgarh and west Madhya Pradesh in August and

**Figs. 8(a-e).** Percentage correct (PC) of heavy rainfall warnings over India during (a-e) summer monsoon months and season as a whole

coastal Karnataka, Arunachal Pradesh and NMMT during the season as a whole. It is even less than 50% over Assam & Meghalaya and NMMT during June, the month of most frequent heavy rainfall events over these subdivisions [Figs. 2(a-e)].

### 3.6. *Percentage correct (PC)*

The PC is more than 70 % for most parts of the country except coastal Karnataka, northeastern states and Sub-Himalayan West Bengal & Sikkim during the season

**Figs. 9(a-e).** Critical success index (CSI) of heavy rainfall warnings over India during (a-e) summer monsoon months and season as a whole

as a whole [Figs. 8(a-e)]. In general, the PC is less over the region with higher frequency of heavy rainfall in different months and season as a whole. Comparing different monsoon months, the number of sub-divisions with  $PC > 90\%$  is maximum in September and minimum in August.

The patterns of PC are dominated by the patterns of C-NON [Figs. 7(a-e)] as the frequency of heavy rainfall events is less [Figs. 2(a-e)]. The PC is less than 50% over NMMT during June, reflecting the pattern of C-NON, though the POD is higher ( $> 50\%$ ) over this region [Figs. 3(a-e)].

**Figs. 10(a-e).** Heidke skill score (HSS) of heavy rainfall warnings over India during (a-e) summer monsoon months and season as a whole

### 3.7. *Critical success index (CSI)*

The CSI is higher ( $> 0.30$ ) over Bihar, Sub-Himalayan West Bengal & Sikkim, Assam & Meghalaya, Orissa, west coast and Madhya Maharashtra and less

( $< 0.20$ ) over southeast peninsula, NMMT, Jharkhand, Saurashtra & Kutch, west Rajasthan, Punjab and J & K during the season as a whole [Figs. 9(a-e)]. The CSI is  $> 0.50$  over Konkan & Goa during June, July and August and over Gujarat region and Sub-Himalayan West Bengal

**TABLE 1**  
**All India verification scores of heavy rainfall warnings during summer monsoon season**

Parameters	Score				
	June	July	Aug	Sep	Season
POD	0.48	0.46	0.40	0.39	0.43
MR	0.52	0.54	0.60	0.61	0.57
FAR	0.62	0.53	0.56	0.55	0.56
BIAS	1.26	0.98	0.91	0.87	0.99
C-NON	0.86	0.83	0.86	0.91	0.87
PC	81	74	76	83	78
CSI	0.27	0.30	0.26	0.26	0.28
HSS	0.31	0.29	0.27	0.32	0.30

& Sikkim during July. The CSI is generally higher over the heavy rainfall prone regions including windward side of hilly regions and the region affected by LPS. It is less over the region with less heavy rainfall events including the regions lying on the lee side of major hill ranges. The number of sub-divisions with lower CSI ( $< 0.20$ ) is maximum in June and with higher CSI ( $> 0.30$ ) is maximum in July.

### 3.8. Heidke skill score (HSS)

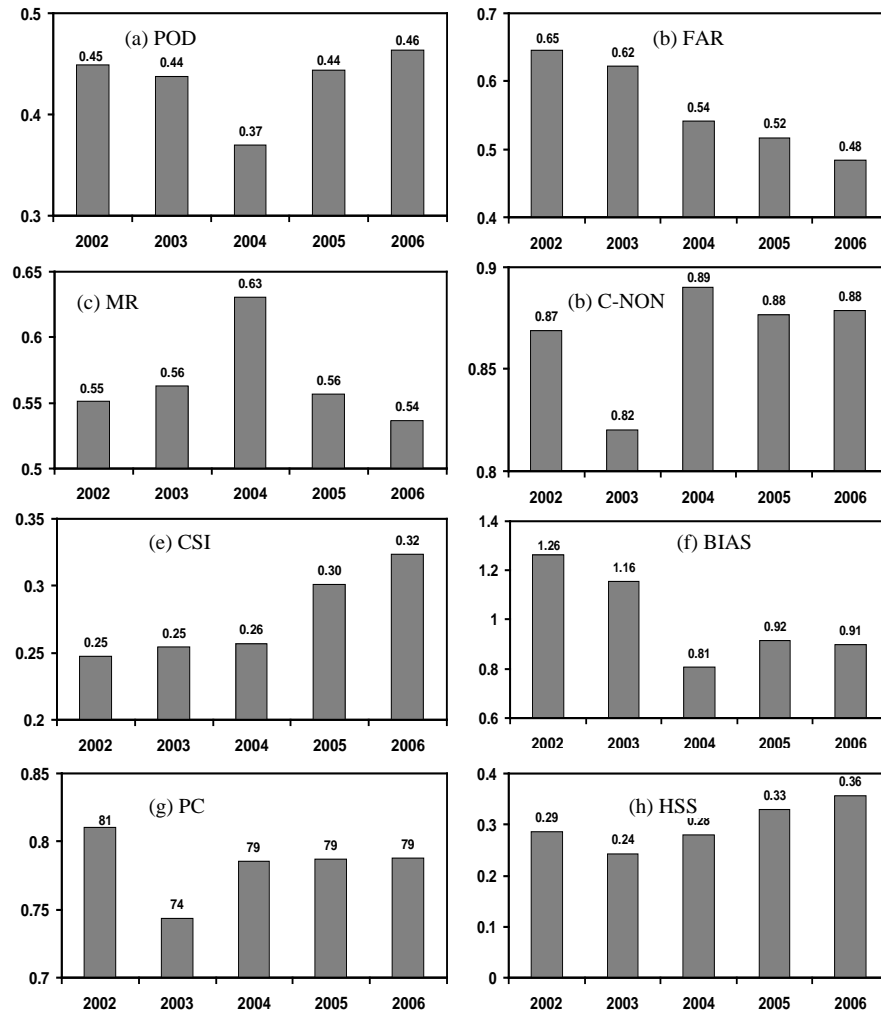
The HSS gives a relative measure of the skill of the forecast compared to random forecast. The HSS is  $> 0.50$  over Madhya Maharashtra, Gujarat region and west Rajasthan in June, Gujarat region in July, Konkan & Goa in August, Madhya Maharashtra and west Uttar Pradesh in September and Gujarat region in the season as a whole (Fig. 10). It is also relatively higher ( $> 0.30$ ) over remaining parts of west coast and some parts of central India including Orissa, east Madhya Pradesh and east Rajasthan during the season as a whole. Hence, the HSS is higher over the regions with more frequent heavy rainfall events and also over the regions of movement of LPS.

The HSS is less ( $< 0.20$ ) over southeast peninsula and NMMT in different months and season as a whole. Hence, the HSS is less over the regions with less heavy rainfall events and the regions lying on the lee side of the major hill ranges. It is also less than 0.20 over J & K during season as a whole and all individual months except September and over Arunachal Pradesh during June, July and season as a whole. The number of sub-divisions with lower HSS ( $< 0.20$ ) is maximum in June and with higher HSS ( $> 0.30$ ) is maximum in July like the CSI.

### 3.9. All India scores

The various score parameters of heavy rainfall warnings considering all the meteorological sub-divisions together, are shown in Table 1. The POD varies between 0.4 and 0.5 with FAR between 0.5 and 0.6 during different monsoon months and season as a whole. The PC varies from 74% in July to 81% in June and is dominated by the C-NON. The CSI varies from 0.26 to 0.30 and HSS from 0.27 to 0.32. All these indicate that there is no significant variation in the score parameters during individual monsoon months and the season as a whole.

The scores during individual years are presented in Figs. 11(a-h). There is gradual improvement in CSI and HSS over the years. It may be mainly attributed to the improved analysis and forecast products available through NWP models to the forecasters in recent years. However, consistent efforts need to be made to reduce FAR and MR and to increase POD of heavy rainfall events. This is possible only either by improving the quality of the NWP models and/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, Petroligis *et al.*, (1997) have shown that probabilistic precipitation predictions are less skilful for predicting extreme weather events, possibly due to less model resolution. Bohra *et al.*, (2006) have also outlined the inadequacy of the numerical guidance, while analyzing exceptionally heavy rainfall over Mumbai on 26 July 2005. Their study indicates that 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 problem of heavy



**Figs. 11(a-h).** Verification measures of heavy rainfall warnings over India during summer monsoon season based on data of 2002-2006. (a) POD, (b) FAR, (c) MR, (d) C-NON, (e) CSI, (f) BIAS, (g) PC, and (h) HSS

rainfall prediction. Further, Maini *et al.*, (2002) have verified the direct model output obtained from NWP models from ECMWF and the statistical interpretation forecast obtained by Perfect Prognostic Method (PPM) based on ECMWF analysis. Their study shows that the statistical interpretation forecast has good skill and is an improvement over direct model output.

#### 4. Conclusions

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

(i) There is a large spatial and temporal variability in the skill scores of heavy rainfall warnings over India

during summer monsoon season. Considering the monsoon season as a whole, the HSS is relatively less ( $<0.20$ ) over the regions with less frequent heavy rainfall like Lakshadweep, southeast peninsula, Vidarbha, Marathwada, J&K, Arunachal Pradesh and NMMT. It is higher ( $>0.50$ ) over Konkan & Goa, Madhya Maharashtra and Gujarat region.

(ii) There has been improvement in the forecast skill with gradual increase in the CSI and HSS over the years mainly due to the NWP models guidance available to the forecasters. However, the FAR and MR are still very high ( $>0.50$ ), especially over many sub-divisions of northwest India, southeast peninsula and NMMT.

(iii) In addition to the inadequacy of NWP models guidance, the poor performance is 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. In addition to improvement of NWP models, the statistical interpretation of the NWP models guidance by suitable linking of the location/grid specific precipitation forecast from the numerical model(s) with the actual precipitation can reduce the subjectivity and hence improve the accuracy of heavy rainfall warning.

#### Acknowledgement

The authors are thankful to Director General of Meteorology, IMD for providing the facilities to carry out this work. The authors also thank Mr. Rattan Kumar, AM-II and Mr. Kalu Ram, AM-I, IMD, New Delhi for their help in the collection of the data from NHAC, IMD, New Delhi.

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