

A diagnostic study of some flood producing rainfall events in Bangladesh with a limited area analysis-forecast system

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सार – इस शोध-पत्र में दक्षिणी पश्चिमी मानसून की अवधि के दौरान बंगलादेश में भारी वर्षा के कारण आने वाली बाढ़ का नैदानिक अध्ययन किया गया है। इस अध्ययन का मुख्य उद्देश्य बंगलादेश के नदी बेसिनों के उर्ध्व प्रवाह वाले भागों में लगातार होने वाली भारी वर्षा की सिनॉप्टिक स्थितियों का पता लगाना है। वर्ष 1987 और 1998 के दौरान हुई सबसे अधिक वर्षा और सबसे अधिक बाढ़ वाले दो वर्षों का भारी वर्षा वाले तूफान के संबंध में अध्ययन किया गया है। ई. सी. एम. डब्ल्यू. एफ. ई. आर. ए.-40 से उनके फिप साइट से डाउनलोड किए गए नैदानिक विश्लेषण के लिए मौसम संबंधी मानचित्र तैयार किए गए हैं। लघु अवधि में वर्षा का प्रतिरूपण करने के लिए फ्लोरिडा राज्य विश्वविद्यालय के सीमित क्षेत्र पूर्वानुमान निदर्श का उपयोग किया गया है। इस निदर्श को क्षैतिज ग्रिड पर आधा डिग्री अक्षांश/देशांतर और ऊर्ध्वाधर में 16 सिगमा स्तरों पर व्यावहारिक बनाने के लिए प्रयुक्त किया गया है। अध्ययन वाले इन वर्षों में बाढ़ लाने वाले वर्षा-तूफानों के लिए उत्तरदायी सामान्य सिनॉप्टिक स्थिति, इन उत्तरी बंगलादेश में उत्तराभिमुखी अक्षांश पर मौसमी मानसून द्रोणी के अक्ष की अवस्थिति और बड़े पैमाने पर परिसंचरण की विसंगतियों के प्रभावस्वरूप उपर्युक्त स्थितियों में स्थिर पाई गई है। सीमित क्षेत्र निदर्श से वर्षा के पूर्वानुमान 24 घंटों और 48 घंटों की पूर्वानुमान अवधियों में प्राप्त हुए हैं जो प्रेक्षित वर्षा वितरण के संबंध में सुसंगत पाए गए हैं।

ABSTRACT. A diagnostic study of flood producing heavy rainfall in Bangladesh during the southwest monsoon period has been carried out. The study focuses on identifying the synoptic situations leading to persistent heavy rainfall within Bangladesh and in the upstream portions of the river basins of Bangladesh. Case studies are carried out in respect of heavy rainstorms in the two most outstanding excess rainfall and flood years 1987 and 1998. The weather maps for diagnostic analysis are prepared from ECMWF ERA-40 Reanalysis data sets downloaded from their ftp site. A limited area forecast model based on Florida State University has been used for simulating the precipitation in short range. The model has been customized to run on half degree Lat./Long. horizontal grid and 16 sigma levels in the vertical. The common synoptic situation responsible for flood producing rainstorms in the years examined is the positioning of the axis of seasonal monsoon trough in a northerly latitude over north Bangladesh and persistence of the above conditions under the influence of large scale circulation anomalies. The limited area model produced precipitation forecasts in 24h and 48h forecast ranges, which were reasonably well placed with reference to the observed rainfall distribution.

Key words – Flood producing rainstorms, Synoptic situation, Diagnostic analysis, Monsoon trough, Land depression, Monsoon depression, Limited area model, Precipitation forecasts, Seasonal scale circulation.

1. Introduction

Bangladesh, known as the country of rivers, is frequently visited by floods, often devastating, during the summer monsoon period. During recent times the country experienced severe floods in 1987, 1988 and 1998 (SMRC, 2003; Quadir *et al.*, 2003). Based on an analysis of the discharge data by Mirza *et al.* (2001), Quadir *et al.* (2003) reported that the discharge levels in the Ganga, Brahmaputra and Meghna river systems attained their highest ever peaks in these years at some locations. An analysis of the seasonal rainfall departure from the long period average over Bangladesh during the monsoon

period revealed that the floods in 1987 and 1998 occurred due to excess rainfall within Bangladesh as also in the upstream portion of the river basins. Fig. 1 shows the year to year time series of the percentage departures of the country average monsoon rainfall of Bangladesh during the two main monsoon months of July & August with reference to the long period average (1971-2000), where the years 1987 and 1998 stand out clearly. The year 1988, on the other hand, did not experience any excess rainfall within Bangladesh and the floods occurred mainly due to the contributions to river discharge from upstream. 1988 was characterised by highly excess rainfall in some of the meteorological sub-divisions of northeast India such as

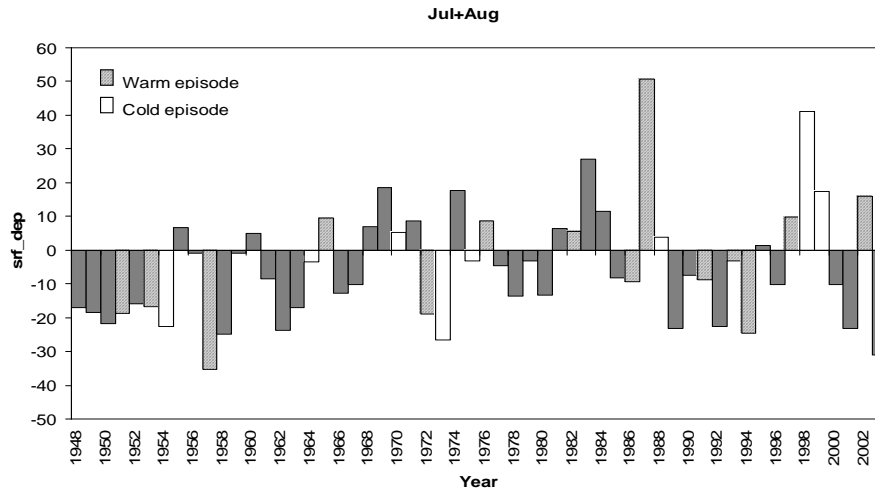


Fig. 1. Monsoon rainfall in Bangladesh during July & August - percentage departures of country average rainfall from long period average (1971-2000); warm and cold episodes refer to the El Niño and La Niña events

Arunachal Pradesh, Assam & Meghalaya and Sub-Himalayan West Bengal & Sikkim that constitute a part of the mighty Brahmaputra and Teesta river basins (SMRC, 2003), which eventually merge with the river systems of Bangladesh. Interestingly, 1987, which was a significant El Niño year and a major drought year in India, turned out to be the most significant excess monsoon and a major flood year in Bangladesh. While the rainfall in Bangladesh by itself was highly in excess during 1987, the adjoining meteorological sub-divisions of northeast India, *viz.*, Arunachal Pradesh, Assam & Meghalaya, Sub-Himalayan West Bengal & Sikkim and even Bihar Plains, which all contribute to the river discharge entering Bangladesh, also recorded large excess (SMRC, 2003), in the backdrop of the large scale drought in other parts of India. 1998 was overall a good and normal monsoon in India. On the other hand, the year 2003, which had a bountiful rainfall in India, had one of the most deficient rainfall in July & August in Bangladesh (Fig. 1). This prompted us to look into the anomalies of the atmospheric circulation in the region *vis-a-vis* the large anomaly in the rainfall distribution in the two neighbouring regions. The objective of this study is to identify the typical synoptic situations leading to flood producing heavy rainfall in Bangladesh with particular reference to the monsoons of 1987 and 1998. We have chosen the episodes of heavy rainstorms in the above two prominent flood years for a diagnostic study.

The study is carried out with the aid of a limited area numerical analysis-forecast system based on the Florida State University (Krishnamurti *et al.*, 1990) model and

implemented in the SAARC Meteorological Research Centre (SMRC) Dhaka for NWP research. Salient features of the FSU model are presented in Table 1. Various versions of this model have been used in tropical prediction experiments by Krishnamurti *et al.* (1979, 1987), Krishnamurti and Ramanathan (1982), Krishnamurti (1985) and Krishnamurti *et al.* (1990). Results of these experiments have amply demonstrated the capability of the FSU model in forecasting the tropical weather systems effectively. A version of this model implemented in India Meteorological Department, New Delhi has been used for tropical cyclone track prediction in conjunction with a bogusing scheme (Prasad *et al.*, 1997).

The SMRC version of the model is run on a horizontal grid resolution of $0.5^\circ \times 0.5^\circ$ Lat./Long. and 16 sigma levels (15 layers) in the vertical on a SUNFIRE V480 system. The basic data sets required for preparing the synoptic maps and the initial and lateral boundary conditions for running the model are drawn from the ECMWF Reanalysis (ERA-40) data available on a coarse resolution of $2.5^\circ \times 2.5^\circ$ Lat./Long. grid on constant pressure surfaces. The gridded fields are interpolated to the limited area model grid and transformed from pressure to the model sigma levels *via* a pressure to sigma converter. The lateral boundary conditions in this study are calculated from 6 hourly analysed fields, the so called perfect boundary conditions. The orography is obtained by smoothing the 30 minute terrain field; the highest point carries a value of about 5400 meters in the Himalayan region.

TABLE 1
Chief characteristics of the limited area model used in SMRC
[based on Florida State University; Krishnamurti *et al.* (1990)]

Dynamics	: Semi-implicit (McGregor and Leslie, 1977); semi-Lagrangian (Mathur, 1983)
Finite differencing grid	: Arakawa C-grid (Mesinger and Arakawa, 1976); staggered in horizontal and vertical; variables u , v , q and T defined at centres of σ layers; vertical velocity and z defined at σ interfaces
Physical processes	: Include shallow and deep moist convection, large scale condensation, air-sea interaction, diffusion processes, planetary boundary layer, radiative processes, surface fluxes based on similarity theory
Horizontal grid resolution	: $0.5^\circ \times 0.5^\circ$ Lat./Long.
Vertical grid resolution	: 16 σ levels (15 layers); 0.05, 0.125, 0.175, 0.225, 0.275, 0.350, 0.450, 0.550, 0.650, 0.750, 0.800, 0.850, 0.900, 0.950, 0.990, 1.0
Lateral boundary conditions	: Updated every six hours
Integration domain	: 30° E to 120° E; 15° S to 45° N
Input variables	: Geopotential, temperature, zonal and meridional components of wind, log of surface pressure
Fixed fields	: Sea surface temperature, albedo, terrain (smooth)
Output variables	: Geopotential, temperature, zonal and meridional components of wind, log of surface pressure, vertical velocity, cumulative precipitation
Basic data for analyses and forecasts	: European Centre for Medium Range Weather Forecasts(ECMWF) ERA-40

The above system has been used in a few case studies of heavy rainstorms during the summer monsoon season in Bangladesh, with particular reference to 1987 and 1998, the two most prominent flood years. The focus of this study is twofold – (i) to identify the typical synoptic situations causing heavy rainstorms in Bangladesh; and (ii) to examine the efficacy of the forecast model in predicting these events in short range time scales. With this end in view we constructed the weather maps on selected days of heavy rainstorms and computed some derived parameters for a diagnostic analysis. The forecast model was run up to 48 hours for rainfall prediction. Results of analyses from a synoptic perspective and model predictions are presented in section 2 and further discussed in section 3. Concluding remarks are given in section 4.

2. Analysis and model forecasts of significant rainstorms during the 1987 and 1998 monsoons

The monsoons of 1987 and 1998 were characterised by several episodes of severe rainstorms resulting in highly excess rainfall over Bangladesh as mentioned

earlier. We identified the dates of severe rainstorms by computing the daily country average rainfall. The country average is simply the arithmetic mean of the available stations on a day. Long series of daily rainfall are available for 34 stations, which were collected from the Bangladesh Meteorological Department. A map showing the locations of rainfall stations in Bangladesh is given in Fig. 2. Figs. 3(a&b) show the plots of daily country average rainfall during the above two years respectively. The day to day rainfall distribution in both the years is marked by occurrence of several peaks in the bar diagram. A high peak in the country average is a reflection of widespread heavy rainfall with many stations reporting high values of 24 hour precipitation, at times exceeding 20 to 30 cm in a continuous spell of several days. The most significant peaks in 1987 occurred in the last week of July, continuing into the beginning of August, and in the last week of August, the latter recording a country average rainfall exceeding 90 mm. The one in the last week of July exceeded 80 mm. The highest peaks in 1998 were comparatively moderate as compared to 1987. The most significant peaks in 1998 occurred in the second week of July and the second week of August. The synoptic

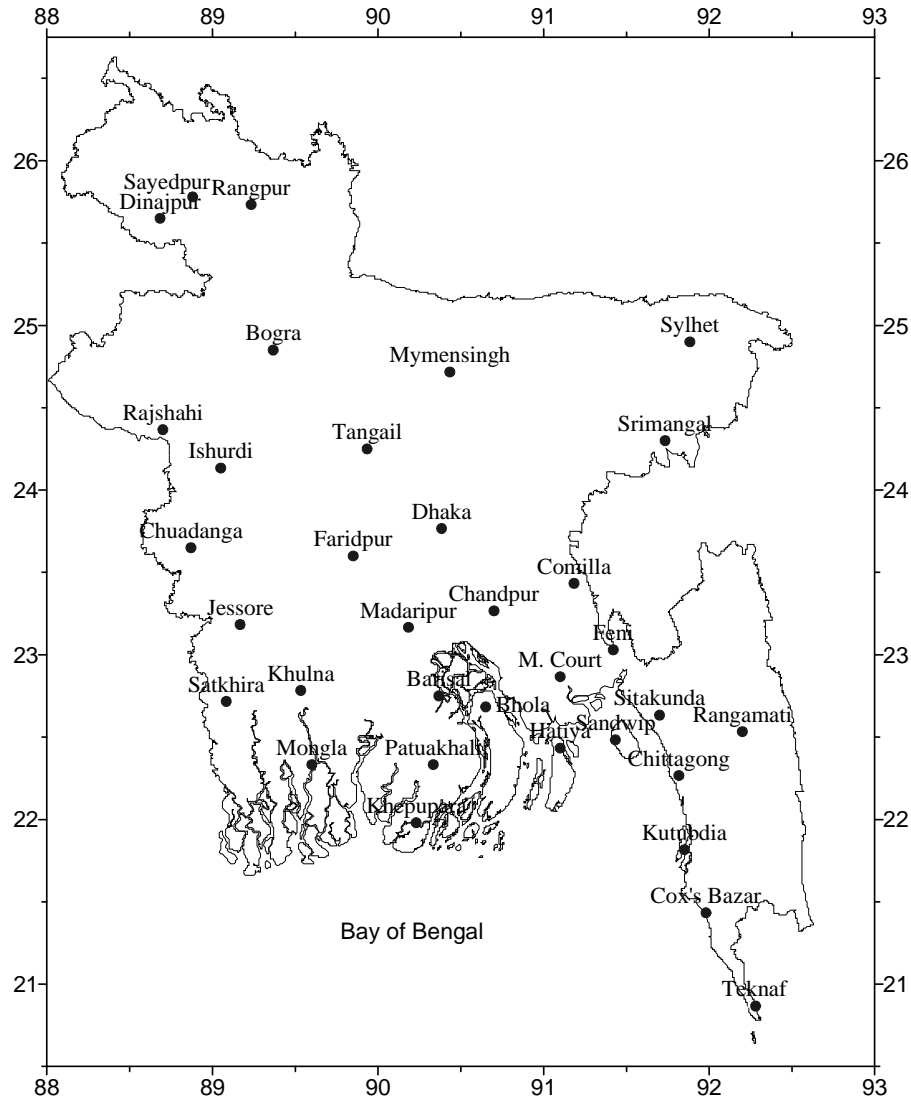


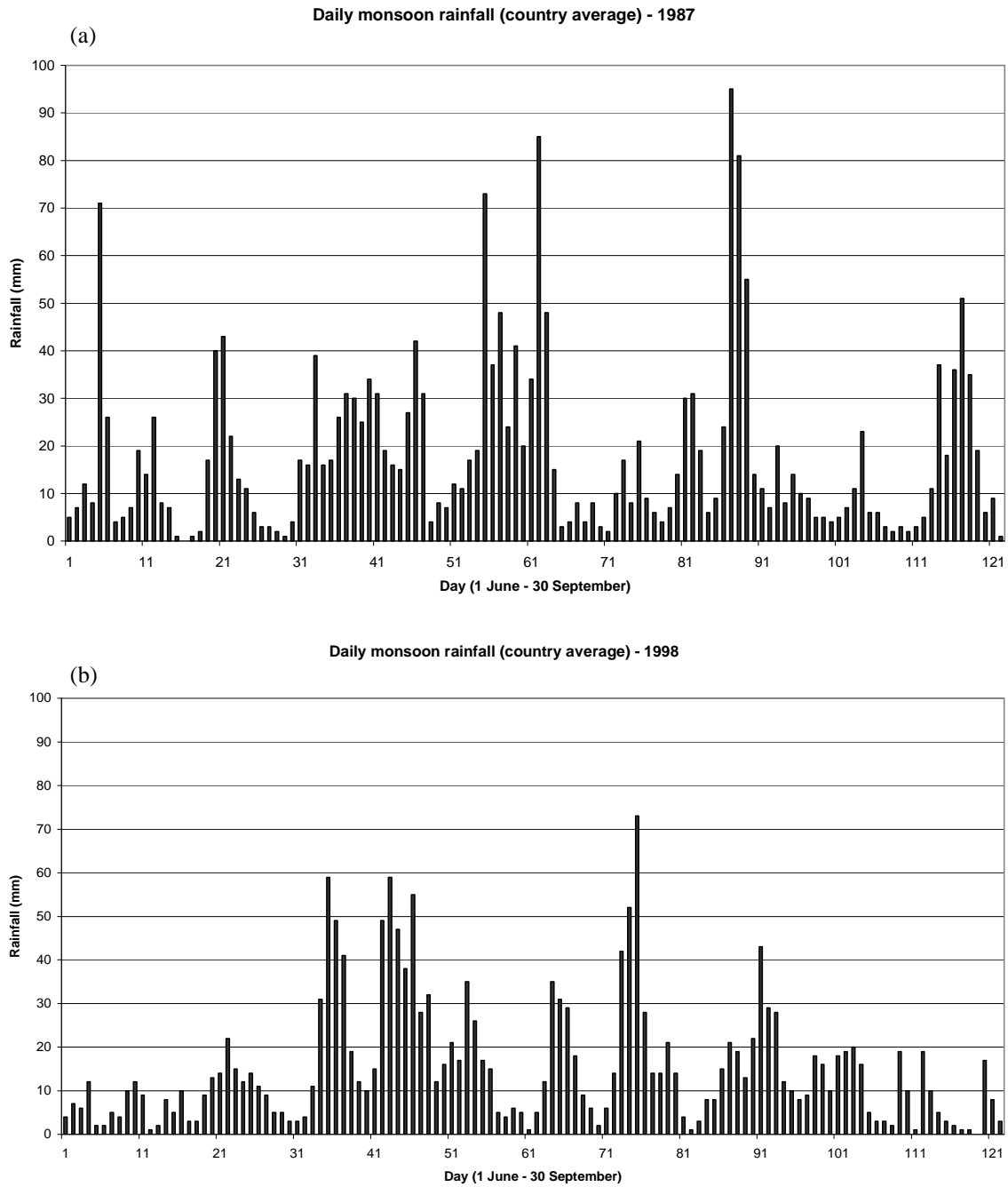
Fig. 2. Map showing locations of rainfall stations in Bangladesh

situations in respect of the above four rain spells are discussed in the following sub-sections.

2.1. Monsoon trough over Bangladesh during last week of July to beginning of August 1987

During the third week of July 1987, a low pressure area appeared over Bangladesh on 17 July (India Met. Dept., 1987). The low shifted slightly southward to north Bay of Bengal on 18 July. It then moved inland and was located over north Orissa and adjoining Bihar Plateau and Gangetic West Bengal on 19th. The low further moved northwest and lay over Bihar, adjoining northeast Madhya

Pradesh and southeast Uttar Pradesh on 20th. It persisted over Bihar on the subsequent three days. Consequent upon movement of the low pressure area from north Bay to Bihar the axis of seasonal monsoon trough got aligned in a northerly position passing across Bangladesh during the last week of July. This is demonstrated in Fig. 4, which shows the mean sea level pressure analysis (mslp) on 24 July 1987. A sharp monsoon trough is seen running across northern parts of Bangladesh and thence eastward across northeastern states of India. A north south trough runs along the east coast of India. The streamline flow at 850 hPa had a prominent reflection of the sea level trough along the east coast (not shown). The flow to the east of



Figs. 3(a&b). Daily monsoon rainfall (country average) in Bangladesh during the monsoon season (a) June to September 1987 and (b) June to September 1998

this trough had a strong northward meridional component causing a large moisture incursion into the Assam and neighbouring areas from Bay of Bengal and striking the hill features in the eastern Himalayas, almost at right

angle, causing strong orographic ascent of moist air. There exists an area of strong accumulation of moisture as seen in the pattern of integrated horizontal moisture flux divergence in Assam and neighbourhood (Fig. 5). The

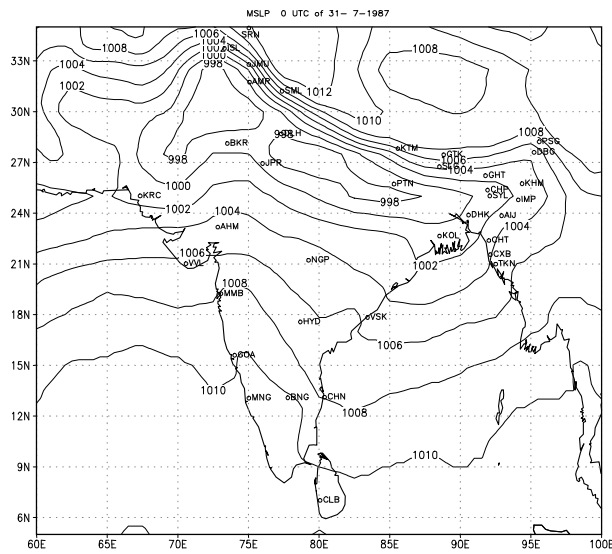
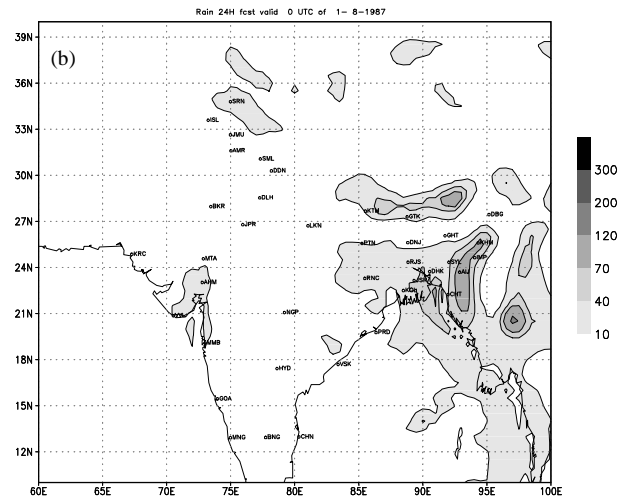
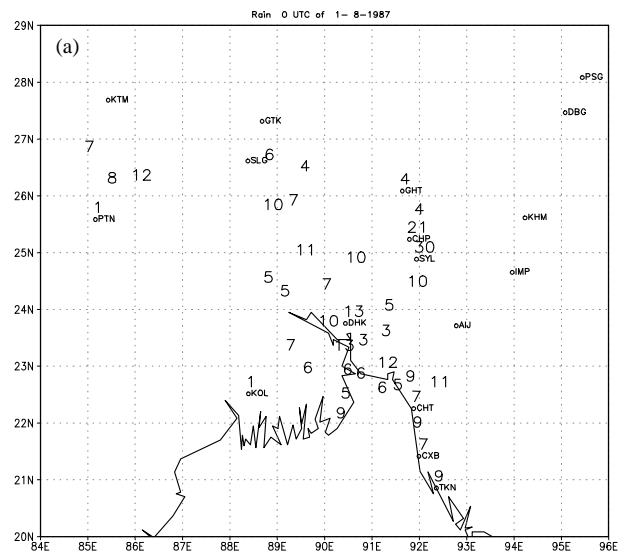


Fig. 7. Mean sea level pressure analysis at 0000 UTC on 31 July 1987 (based on ECMWF ERA-40)

The flow at 500 hPa and 300 hPa was characterised by southward displacement of the subtropical ridge from its position, which in the normal lies along about 28-30 deg. latitude in the Indian longitudes (not shown). At 500 hPa a centre of anticyclonic circulation lay over central India near Nagpur, embedded in the subtropical ridge. The centre of anticyclonic circulation at 300 hPa was over Gangetic West Bengal close to Kolkata. The 500 hPa flow exhibited a middle latitude westerly wave apparently moving across western Himalayas with a cyclonic circulation located close to Himachal Pradesh over north India. The totality of synoptic situation with the westerlies prevailing in the lower troposphere, shifting of the middle and upper tropospheric subtropical ridge southward and movement of a middle latitude westerly wave across extreme northern India resembled that of a typical ‘break’ monsoon condition in the Indian monsoon system. The synoptic setting was thus very favourable for heavy precipitation in the northeastern region of India and neighbourhood. The heavy rain spell in Bangladesh during the above period was thus found to be associated with the monsoon trough located in a northerly position, close to the foothills of eastern Himalayas and the upper air flow typical of a ‘break’ monsoon situation.

The Forecast model was run based on the initial conditions of 24 July with lateral boundary conditions calculated from analyses at 6 hourly intervals. The 48 hour (cumulative) predicted rainfall, valid for 26 July 1987, is presented in Fig. 6(a). The model produced heavy rainfall in the areas covering Assam & adjacent states and Bangladesh, consistent with the synoptic



Figs. 8(a&b). (a) 24 hour rainfall (cm) as observed on 1 August 1987 and (b) 24 hour predicted rainfall (mm) based on initial conditions of 31 July 1987 and valid on 0000 UTC of 1 August 1987

patterns and the areas of heavy moisture convergence. Fig. 6(b) contains the 24 hour observed rainfall as on 25 July and 26 July for verification. Widespread heavy rainfall along the coastal areas of Bangladesh, influenced by orography, as well as northern and central parts was the prominent feature.

The monsoon trough stayed north for a considerably long period of about 10 days through the beginning of August. As a corroboration of this statement, the mean sea level pressure analysis on 31 July 1987 is presented in Fig. 7, which shows the monsoon trough persisting in the same location across north Bangladesh. The observed rainfall distribution on 1 August (the day of peak in the country average rainfall in 1987) is shown in Fig. 8(a).

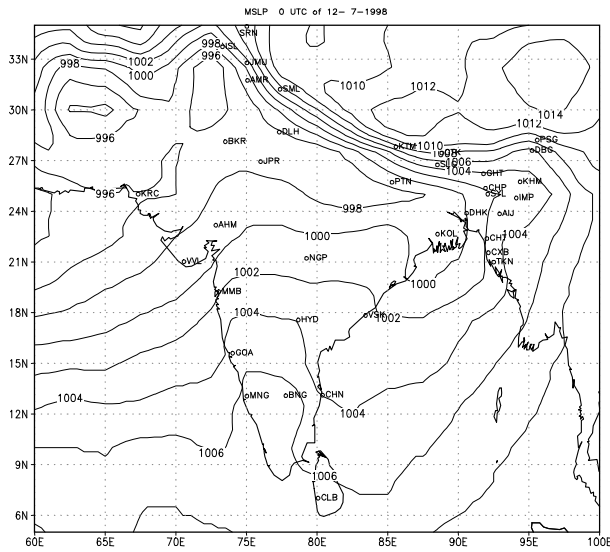


Fig. 11. Mean sea level pressure analysis at 0000 UTC on 12 July 1998 (based on ECMWF ERA-40)

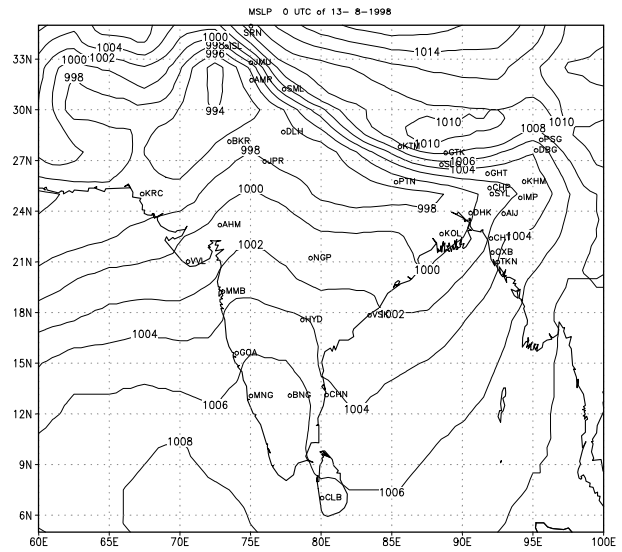


Fig. 12. Mean sea level pressure analysis at 0000 UTC on 13 August 1998 (based on ECMWF ERA-40)

pertinent to state here that the maps presented in these analyses are constructed from the post processed fields after interpolation from a coarse resolution of 2.5×2.5 deg. Lat./Long. to 0.5×0.5 deg. Lat./Long. In this process the geometry and shape of the isobaric fields is likely to get distorted. This is reflected in somewhat elongated shape of the depression and its centre a little displaced from the synoptic centre. Nevertheless the synoptic patterns have been well reproduced from the reanalysis data sets *via* the post processing procedures adopted in this study. In an attempt to trace the origin of this land depression, we constructed the analysed daily synoptic maps for the preceding few days – upto 20th of August. The origin of the disturbance could be traced to South China Sea. A tropical depression existed in the South China Sea on 20th August. The disturbance moved westnorthwestward and, travelling across Indochina peninsula, gradually lost strength. It arrived over Bangladesh territory on 25 August, where it again intensified into a land depression. The depression travelled further westward and was located over Bihar Plateau and adjoining Gangetic West Bengal on 27th; Bihar Plateau and adjoining north west Madhya Pradesh on 28th; and northwest Madhya Pradesh and adjoining south Uttar Pradesh on 29th (India Met. Deptt., 1987). It weakened into a well marked low pressure area on 30 August and finally dissipated over the plains of west Uttar Pradesh.

The above system caused heavy rainfall in the southern and the hilly southeastern region of Bangladesh.

The streamline pattern at 850 hPa exhibited a strong westerly flow striking the Arakan range of hills. The 24 hour predicted rainfall based on the initial conditions of 25 August and valid for 0000 UTC of 26 August is shown in Fig. 10(a). A plot of 24 hour rainfall as recorded on 26 August 1987 is shown in Fig. 10(b). The southern parts of Bangladesh, south of the depression, received very heavy rainfall in this case, while the northern and central parts got only moderate rainfall. The role of orography in producing heavy rainfall along the coastal areas is clearly brought out.

2.3. Monsoon trough over Bangladesh during July & August 1998

The monsoon season of 1998 was also characterised by quite a few active rain spells during July and August. The peaks in the daily distribution of country average rainfall occurred on 5 July (59 mm), 13 July (59 mm) and 14 August (73 mm). The analysis of synoptic situations corresponding to these heavy rainstorms showed that these events were also associated with the monsoon trough running across Bangladesh. The mean sea level pressure analyses on 12 July and 13 August 1998 are shown in Figs. 11 and 12 respectively as illustrative examples. The analysis pattern is similar to the one presented earlier in respect of the July 1987 event, with a trough aligned along the east coast of India and the resulting southerly moist flow from the Bay of Bengal penetrating into Bangladesh. The flow pattern at 850 hPa also exhibited similar features as in July 1987. In this particular case though the axis of seasonal monsoon trough was in a northerly position, it could not be described as a break monsoon situation. On

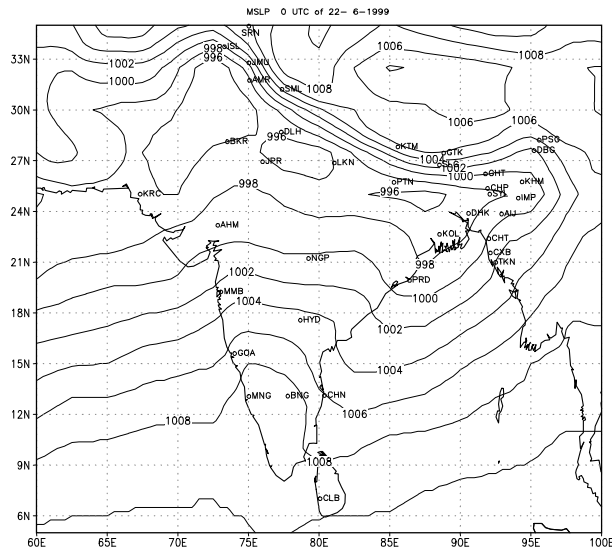


Fig. 13. Mean sea level pressure analysis at 0000 UTC on 22 June 1999 (based on ECMWF ERA-40)

the contrary, the upper air flow pattern was typical of a strong monsoon condition. The 500 hPa flow on 13 August was characterised by a prominent east west trough along about 24 deg. north with an embedded circulation over central India. This was a reflection of the typical monsoon trough sloping southward with height in a strong monsoon situation. The flow at 300 hPa was deep easterly over the north Bay of Bengal and neighbourhood, with the axis of the subtropical ridge line located farther north, again typical of a strong monsoon condition. Thus the heavy rain spells in these instances during 1998 were associated with a strong monsoon situation over India with the surface monsoon trough in a favourable northerly latitude. This is in sharp contrast with the synoptic situation in July 1987, when the surface monsoon trough located in a similar position over north Bangladesh was coupled to a break monsoon type upper air flow as described in a previous section.

3. Discussion

It turns out from the analysis of synoptic situations in respect of the selected heavy rainfall events in the two outstanding excess monsoon rainfall years 1987 and 1998 that the typical synoptic setting for heavy rainfall in Bangladesh is the positioning of the axis of seasonal monsoon trough in a northerly latitude passing across the country's territory. The shifting of the monsoon trough northward usually takes place in the wake of a monsoon depression or a low pressure area from the Bay of Bengal moving across central and northern parts of India. In one of the cases analysed in the present study, the surface monsoon trough located over northern Bangladesh, close

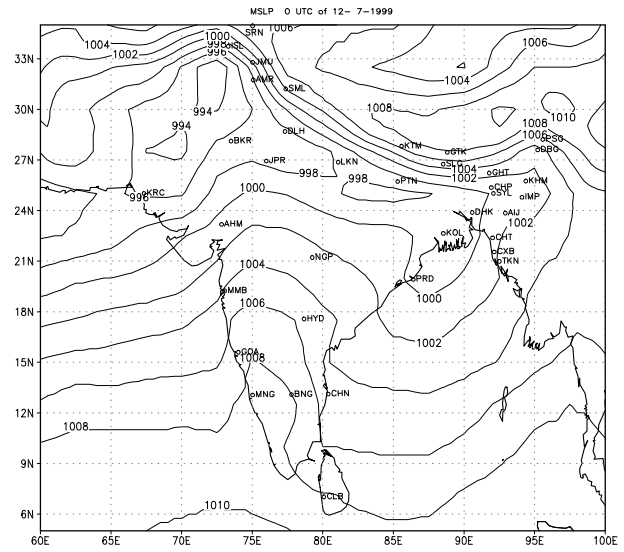


Fig. 14. Mean sea level pressure analysis at 0000 UTC on 12 July 1999 (based on ECMWF ERA-40)

to the foothills of Himalayas, was accompanied by the upper air flow pattern typical of a break monsoon situation in India. A middle tropospheric cyclonic circulation was seen over western Himalayas across extreme north India and the upper tropospheric subtropical ridge line (Tibetan High) was displaced southward with the centre of anticyclonic circulation at 300 hPa positioned over Bangladesh and neighbourhood. This was the case in July 1987. It may be recalled that 1987 was a major drought year in India. In another case, *i.e.*, in August 1998, with the surface monsoon trough located in the same position as in 1987 over north Bangladesh, the upper air flow pattern was typical of a strong monsoon situation, *viz.*, the monsoon trough extending upto the middle tropospheric levels, sloping southward with height, and the subtropical ridge in the upper troposphere located in its normal position in a northerly latitude. 1998 was a good monsoon year in India as well as Bangladesh.

In yet another case a tropical depression moved westward across Indochina peninsula and arrived over Bangladesh as a weak disturbance. It developed into a land depression after reaching Bangladesh. The depression produced heavy rainfall in south Bangladesh, particularly in the coastal hill areas.

In further support of our argument about the northward position of the monsoon trough being a favourable condition for occurrence of heavy rainfall in Bangladesh, we picked up some more events of widespread heavy rainfall during the years 1999 and 2001, which had significantly above normal rainfall during July and August (Fig. 1), with some high peaks in the daily

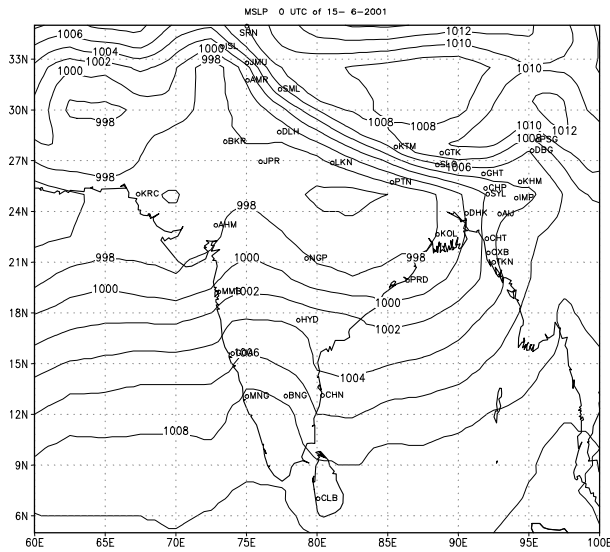


Fig. 15. Mean sea level pressure analysis at 0000 UTC on 15 June 2001 (based on ECMWF ERA-40)

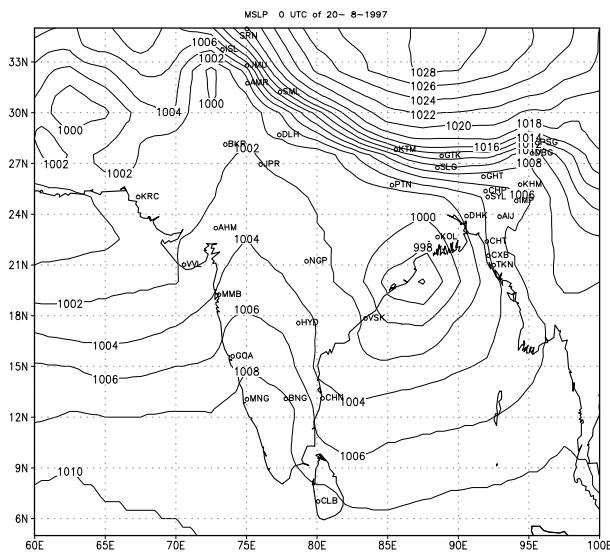
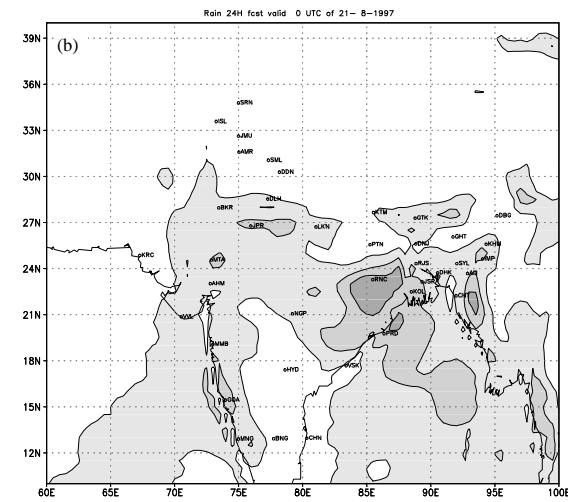
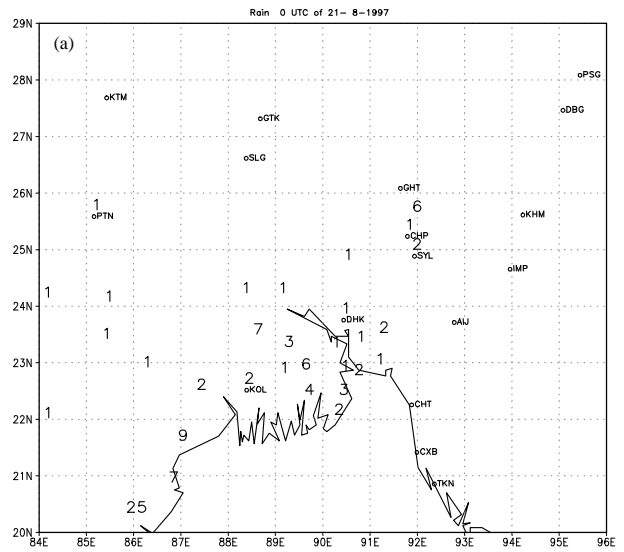


Fig. 16. Mean sea level pressure analysis at 0000 UTC on 20 August 1997 (based on ECMWF ERA-40)

time series of country average rainfall (not shown). These peaks were, however, short lived unlike 1987 and 1998. These periods were the third week of June 1999, the second week of July 1999 and the third week of June 2001. The mean sea level pressure analyses on the selected days, *viz.*, 22 June 1999, 12 July 1999 and 15 June 2001 are presented in Figs. 13-15. In all the above



Figs. 17(a&b). (a) 24 hour rainfall (cm) as recorded on 21 August 1997 and (b) 24 hour predicted rainfall (mm) based on initial conditions of 20 August 1997 and valid 0000 UTC of 21 August 1997

cases the monsoon trough is seen to be located in a northerly position, a situation similar to the cases presented during 1987 and 1998.

It would appear from the illustrations presented above that a prolonged residence of the axis of the monsoon trough in a northerly latitude across north Bangladesh is the primary factor leading to persistent heavy rainfall in the country.

It would be necessary to corroborate the inference in the preceding paragraph by exemplifying the rainfall distribution in the contrasting synoptic situation, when the monsoon trough is positioned in a southerly latitude with its eastern end shifting to the head Bay of Bengal. This is usually considered an active monsoon condition for the Indian monsoon rainfall and is generally a precursor to the formation of a monsoon depression in the Bay of Bengal. The case in example is the monsoon depression of August 1997 in Bay of Bengal. The depression formed in the northwest Bay on 20 August and moved inland. It had a long track across central and northwest India. The mslp analysis on 20 August 1997 is presented in Fig. 16. The flow at 850 hPa over the territory of Bangladesh was southeasterly and parallel to the hill features in the coastal areas. Fig. 17(a) shows the observed rainfall distribution over Bangladesh and neighbourhood as reported on 21 August. It would be seen that the rainfall over Bangladesh, which lies entirely to the north of the monsoon trough in this case, was only light to moderate. This distribution is significantly different from the one that occurred with the synoptic situations described in section 2, *viz.*, the monsoon trough passing across north Bangladesh. The observed rainfall distribution here is in conformity with the well known feature of a monsoon depression, where heavy rainfall is mostly confined to the south of the westward moving track due to the maximum convergence there. The northern sector has strong easterly flow in the lower troposphere and the rainfall is minimal, more often even dry weather. The forecast model was run on the initial conditions of 20 August. The 24 hr forecast precipitation from the model, shown in Fig. 17(b), matches with the observed rainfall distribution to a fair degree as far as spatial distribution is concerned. The predicted rainfall distribution over Bangladesh is light to moderate as in the observed distribution. The small patch of rainfall seen to the right of the Chittangong-Cox's Bazar coast is due to orographic influence.

As a natural corollary to the above findings in regard to the distribution of rainfall over Bangladesh being controlled by the position of the monsoon trough, one would be led to think that the exceptionally high seasonal scale anomaly of the monsoon rainfall in Bangladesh during 1987 and 1998 would have been the result of super-synoptic seasonal scale anomalies in the position of the monsoon trough. With this end in view we constructed the monthly mean and anomaly maps of some flow variables using the NCEP/NCAR Reanalysis data sets. On examination of the mean flow pattern at 700 hPa it was found that in both the years there existed a well marked low in the contour field in the eastern Himalaya's

foothills north of Bangladesh. A noteworthy contrast in the two maps, however, was that a well defined trough ran from the contour low across central parts of India to the north Arabian Sea in 1998. This was indicative of strong monsoon conditions and 1998 was a good monsoon year both in Bangladesh and India, as mentioned earlier. On the other hand, during 1987, there was no east-west trough in the contour pattern, a north-south trough from the centre of the contour low to head Bay of Bengal was prominently seen, and the flow over central and northwestern parts of India was northerly. 1987 was an exceptional year in that it was a major drought year in India and an exceptionally high rainfall year in Bangladesh. In further support of our hypothesis about the position of monsoon trough controlling the monsoon rainfall in Bangladesh, we further examined the mean monthly contour field for the month of July during 2003, which was an exceptionally poor monsoon year in Bangladesh with one of the lowest rainfall deficiencies in the two main monsoon months of July and August (Fig. 1). By contrast, 2003 was a bountiful monsoon in India. It was interesting to see that the contour field had a markedly symmetrical east-west oriented monsoon trough running across the breadth of the north peninsular India south of 25 degree north latitude, which was in sharp contrast to the patterns of 1987 and 1998. A well defined low existed over Orissa and neighbourhood. Bangladesh lay to the north of this trough and in a southerly flow regime east of the low. Similar type of circulations at 700 hPa were seen in the months of August in all the above three years, thus making up the anomalies of a seasonal time scale. It was easy to infer that the anomalies in the flow pattern during the three exceptional years of monsoon rainfall in Bangladesh would have been the main contributory factor in shaping the realised rainfall distribution on the seasonal time scale.

4. Concluding remarks

The focus of this study was to identify the synoptic situations responsible for causing persistent heavy rainfall and consequent floods in Bangladesh during the southwest monsoon seasons of the two outstanding excess rainfall years 1987 and 1998. The synoptic weather maps were constructed from the ECMWF ERA-40 data sets. The weather maps prepared from the above data sets faithfully reproduced the flow patterns, which matched the descriptions of weather systems in the published literature such as Indian Daily Weather Reports. The analysis of synoptic situations in respect of selected heavy rainfall events in the above two years showed that the typical synoptic setting for heavy rainfall in Bangladesh is the

positioning of the axis of seasonal monsoon trough in a northerly latitude passing across northern parts of Bangladesh. The surface monsoon trough located over northern Bangladesh may either be associated with a typical break monsoon situation in India as happened in 1987 or it may be associated with a strong monsoon situation as in 1998. 1987, which was a major drought year in India, was one of the highest excess rainfall years in Bangladesh. 1998 was a good monsoon year in India as well as Bangladesh. The monsoon trough may often go into a quasi-stationary mode, persisting over the area for a long duration. This situation may cause persistent heavy rainfall within Bangladesh and the catchment areas upstream, leading to floods. The years 1987 and 1998, in particular, witnessed a situation in which the persistence of monsoon trough in its northerly position was prominently reflected even in the mean monthly maps of flow pattern. This obviously suggested that the above anomaly of the synoptic situation happened on a seasonal time scale and that it was an interplay of global scale circulation anomalies responsible for creating quasi-stationarity of the monsoon trough in a northerly position. These aspects need to be investigated from the point of view of long range forecasting of monsoon rainfall.

A land depression may sometimes form over Bangladesh, which may have its origin farther east over South China Sea. This is a favourable situation for occurrence of heavy rainfall in south Bangladesh and the coastal belt off Arakan coast. The study showed that when a depression forms in its usual position over north Bay of Bengal with the territory of Bangladesh lying to its north and east, the rainfall over the country is only light to moderate, which is in conformity with the typical structure of a monsoon depression.

The limited area forecast model was run for short range forecasts of precipitation during the selected days of heavy rainfall occurrence. The forecasts produced by the model were reasonably placed in regard to simulating the observed areas of rainfall although the predicted magnitudes remained underestimated. The role of orography in modulating the rainfall predictions by the model was prominently brought out.

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