Prediction of monsoon rainfall with a nested grid mesoscale limited area model

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At the India Meteorological Department (IMD), New Delhi, a 12-level limited area model with 100 km horizontal resolution has been in use for weather forecasting. The present study uses this model together with a higher horizontal resolution (50 km) and vertical resolution (16-levels) model to examine the impact of increased resolution to simulate mesoscale features of rainfall during monsoon disturbances. The model was run for 22 days in the month of August 1997 and one week in September 1997 during three monsoon depressions and one cyclonic storm in the Bay of Bengal. The model results are compared with observations. The study shows that the model can capture mesoscale convective organization associated with monsoon depression.

1. Introduction

Indian monsoon rainfall is dominated by meso-β type disturbances, such as orographic rainfall along the west coast (Western Ghats) of India, and synoptically induced mesoscale convective systems during the passage of monsoon low pressure system. Our recent study (Roy Bhowmik and Prasad 2001) shows that the present operational limited area model at the India Meteorological Department (IMD), New Delhi, with horizontal resolution of 100 km and 12 sigma levels in the vertical, though able to reproduce spatial and temporal pattern of monsoon rainfall reasonably well, underestimates orographic rainfall over the west coast of India. The underestimation of orographic rainfall could be due to the terrain at the model resolution not being high enough. The model also overestimates rainfall associated with monsoon circulations. These shortcomings of the operational model have motivated us to take up the present study.

Availability of fast computer systems has led a number of groups to work on different versions of numerical models for mesoscale prediction. Krishnamurti *et al* (1995, 1998) noted that the Florida State University Global Spectral model at the increased resolution of T-213 (transform grid separation of 50 km over tropics) with the incorporation of physical initialization procedure is able to capture the organization of mesoscale convection in the forecast through medium range time scale. Regional models are favoured over the global models for mesoscale regional prediction because their resolution can be increased without much computational expenditure. The Colorado State University, USA developed a comprehensive mesoscale modelling system called Regional Atmospheric Modelling System (RAMS) and made a number of experiments for simulation of mesoscale convective system using different versions of RAMS (Pielke *et al* 1992). Comparing results between the hydrostatic version of RAMS at resolution 80 km and non-hydrostatic version of the model at resolution 25 km, they noted that mesoscale systems could be simulated well with a hydrostatic model. The National Center for Atmospheric Research (NCAR) and the Pennsylvania State University jointly developed a non-hydrostatic fifth generation mesoscale model called MM-5 (Guo and Chen 1993; Dudhia 1993) which is very flexible to use and can be run at different resolutions normally ranging from 50 to 15 km with various (optional) cumu-

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lous parameterization schemes. Many researchers (Black 1994; Mesinger 1996) are working on the mesoscale Eta model. The model has been in operation at the National Center for Environmental Prediction (NCEP), USA. A comparative performance of a few regional models (also called limited area models), namely RAMS, MM-5, Navy Operational Regional Atmospheric Prediction System (NORAPS), and Re-locatable Window Model (RWM) was reported by Cox *et al* (1998). The study ranks RAMS marginally ahead of MM5. Krishnamurti *et al* (2000) have recently introduced a multimodel super-ensemble technique that shows a major improvement in prediction accuracy when results of numerical models are examined as an ensemble.

In India, limited area model (LAM) is being used in research and for operational forecasting (Sarkar and Bedi 1987; Mohanty *et al* 1989, 1990; Abraham *et al* 1996; Prasad *et al* 1997; Roy Bhowmik and Prasad 2001). Improved mesoscale forecast over the Indian region from the use of MM-5 and RAMS at increased resolution has been reported (Patra *et al* 2000; Mohanty and Mandal 2003). But these results are based on only a few case studies. They require more evaluation before making them operational.

The aim of this paper is to examine the impact of model resolution on simulation of mesoscale rainfall features in the presence of monsoon disturbances. The model used in this study is the upgraded version of the operational model of IMD with horizontal resolution of 50 km and 16 sigma levels in the vertical as fine mesh grid (FGM) and the operational run as coarse mesh grid (CGM). The model is run for 24 hours forecast daily based on 00 UTC observation for 22 days in the month of August 1997 and one week in September 1997. Three monsoon depressions and one cyclonic storm over the Bay of Bengal were observed during this time. The experiment results of 24 hours forecast run are compared with reference to those of the operational model and observations. The description of the model is given in section 2 and the design of the experiment in section 3. The synoptic conditions and comparison of corresponding forecast rainfall from the two models at different resolutions are discussed in section 4 and finally conclusions are presented in section 5.

2. Description of the model

The forecast model is a Florida State University based semi-implicit, semi-Lagrangian, multi level primitive equation model cast in sigma coordinate and staggered Arakawa C-grid in the horizontal. The model consists of the usual equations of motion, thermodynamic energy equation, mass continuity equation, moisture continuity equation, hydrostatic equation and equation of state.

The model includes a number of physical processes such as cumulus convection (modified Kuo; Krishnamurti *et al* 1983), shallow convection (Tiedke 1984), large scale condensation, atmospheric boundary layer (Monin-Obukhov formulation of surface layers with stability dependent vertical diffusion in mixed layer), radiation (Harshvardan and Corsetti 1984; Lacis and Hansen 1974) and envelope orography (Wallace *et al* 1983). Further details of the model formulation can be found in Krishnamurti *et al* (1989).

Horizontal resolution of the coarser grid (operational) model is $1^\circ \times 1^\circ$ latitude/longitude and 12 equi-spaced sigma levels (1.0 to 0.05) in the vertical. The orography prescribed in the model is smoothened by a nine point smoother to prevent instability due to steep gradients of terrain over the Himalayan region. The other features of the model include time dependent lateral boundary conditions and dynamic normal mode initialization (Sugi 1986). The model is run up to 48 hours, twice daily initialized with 00 UTC and 12 UTC observations. Lateral boundary conditions of the model are from the global spectral model (T-80/18L) run of the National Center for Medium Range Weather Forecasting (NCMRWF), New Delhi and are updated every 12 hours. The time step of the model is 900 seconds.

2.1 *Analysis procedure*

The operational analysis procedure of the India Meteorological Department (IMD) consists of real time processing of data received on Global Telecommunication System (GTS), decoding and the quality control procedure is handled by AMIGAS software and a multivariate optimum interpolation scheme. The first guess field for running the analysis is obtained online from the global forecast (T-80/18L) run of the National Center for Medium Range Weather Forecasting (NCMRWF), New Delhi.

The input data used for analysis consist of surface, upper air, aircraft and satellite observations. These are extracted and decoded from raw GTS datasets. All the data are quality controlled and packed into a special format for objective analysis.

The methodology applied for objective analysis is the statistical 3-dimensional multivariate Optimum Interpolation (OI) scheme (Dey and Morone 1985). The variables analyzed in this scheme are geopotential $(z), u$ and v components of wind and specific humidity. Temperature (T) field is derived from geopotential field hydrostatistically. Analysis

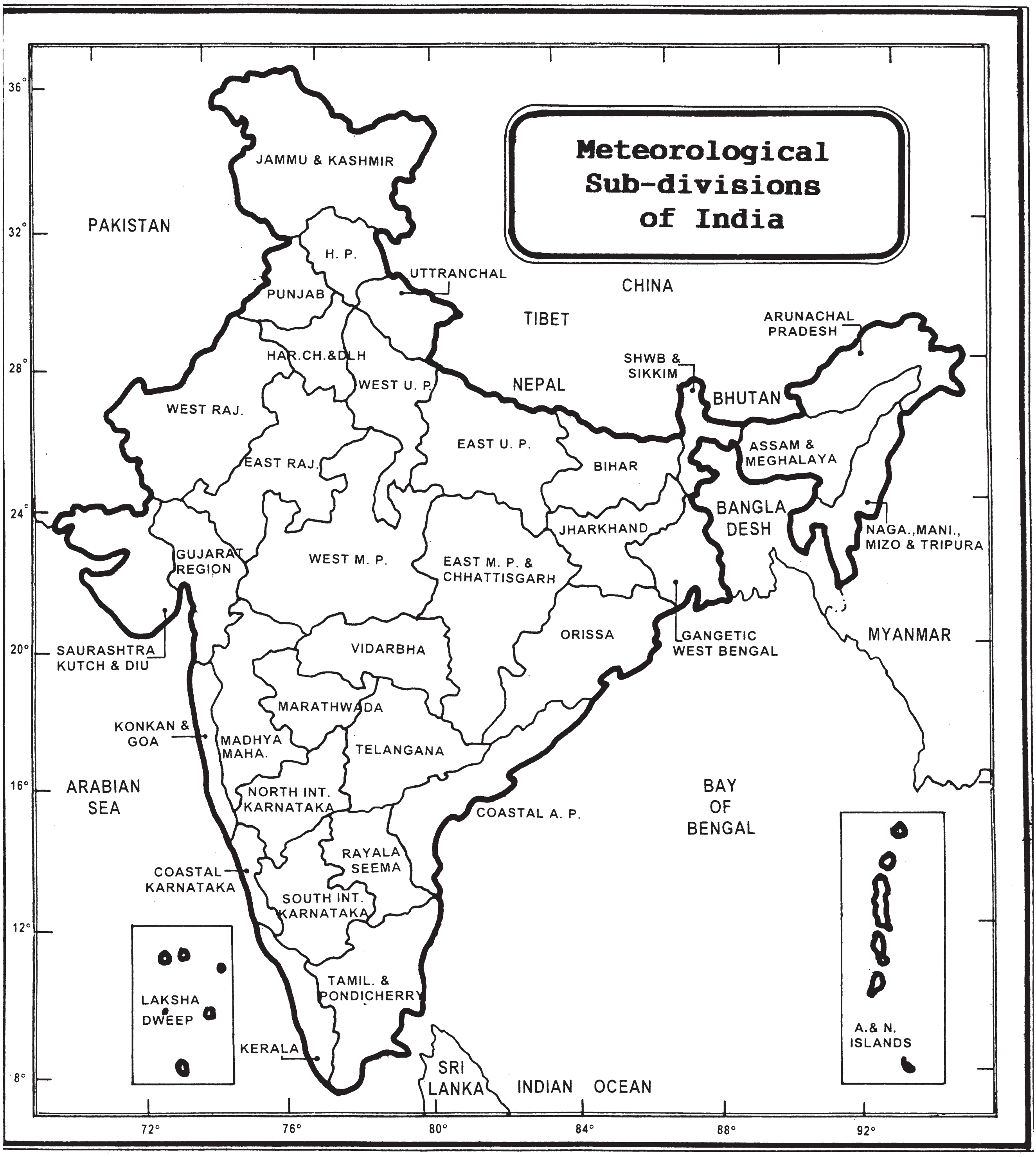


Figure 1. Meteorological subdivisions of India.

is carried out on 12 sigma (pressure divided by surface pressure) surfaces 1.0, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, 0.1, 0.07, 0.05 in the vertical and on $1^\circ \times 1^\circ$ horizontal latitude/longitude grid for a regional or limited horizontal domain covering the domain from latitude 30°S to 60°N and longitude. 0° to 150°E.

3. The design of experiments

For the present version of the model, FGM has the horizontal resolution 0.5° latitude/longitude with 16 sigma levels in the vertical. As boundary layer plays a very important role in low level atmospheric processes associated with monsoon, 7 levels out of

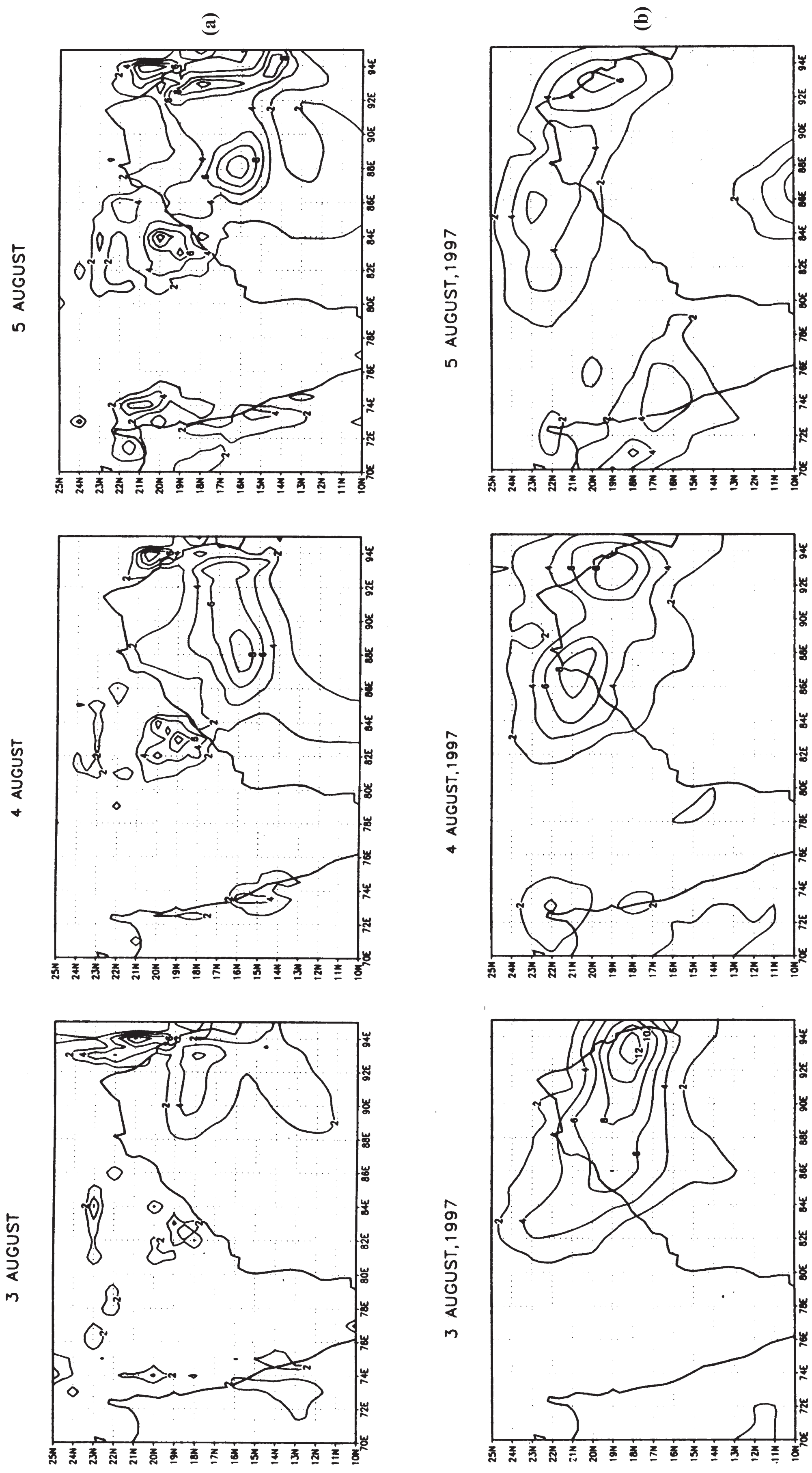


Figure 2(a, b). *(Continued)*

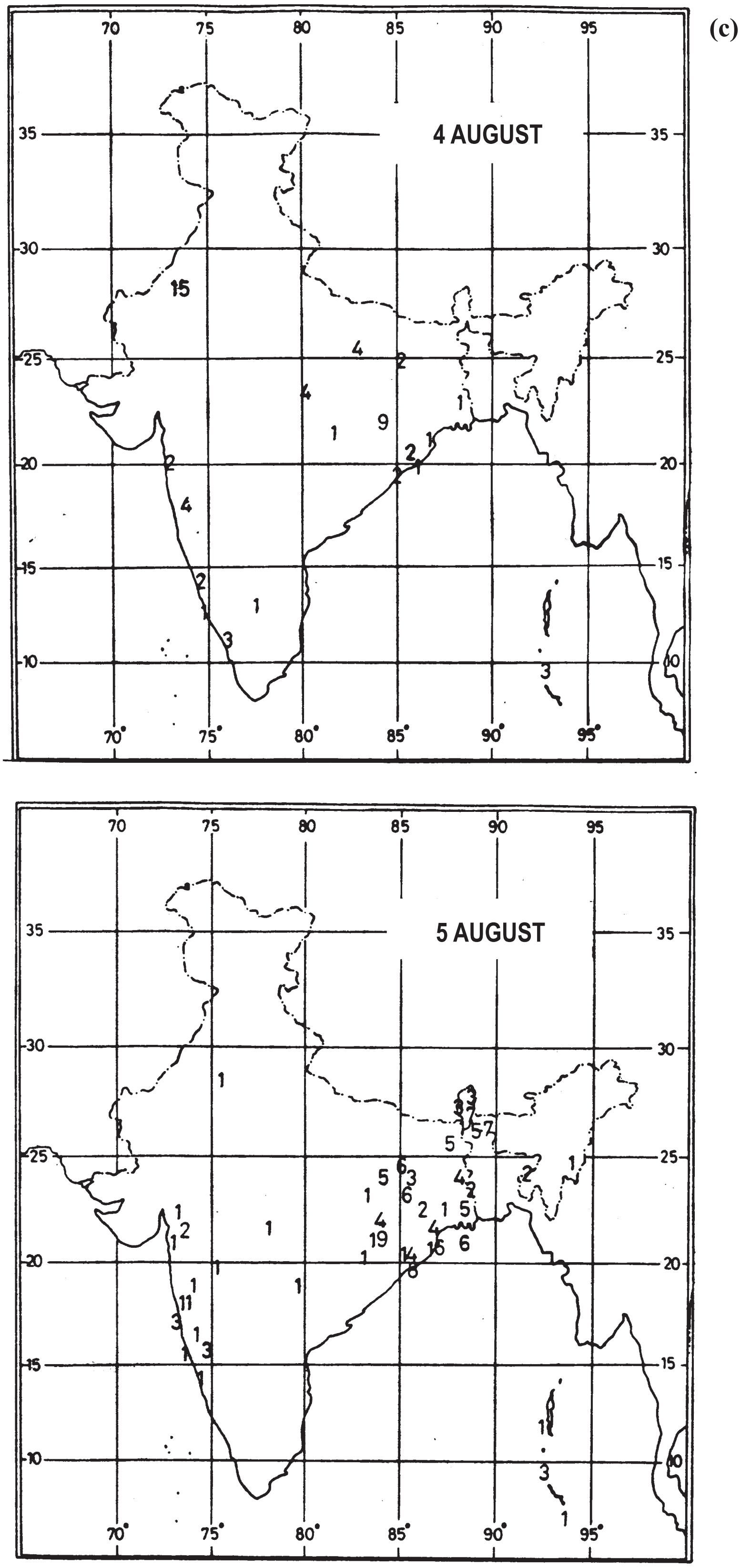


Figure 2. **(a)** 24 hours forecast (0.5 × 0.5) rainfall in cm ending at 00 UTC of 3rd August, 4th August and 5th August 1997; **(b)** same as (a) corresponding to forecast (1 × 1) and; **(c)** 24 hours rainfall observations (cm) from land raingauge stations ending at 03 UTC of 4th and 5th August.

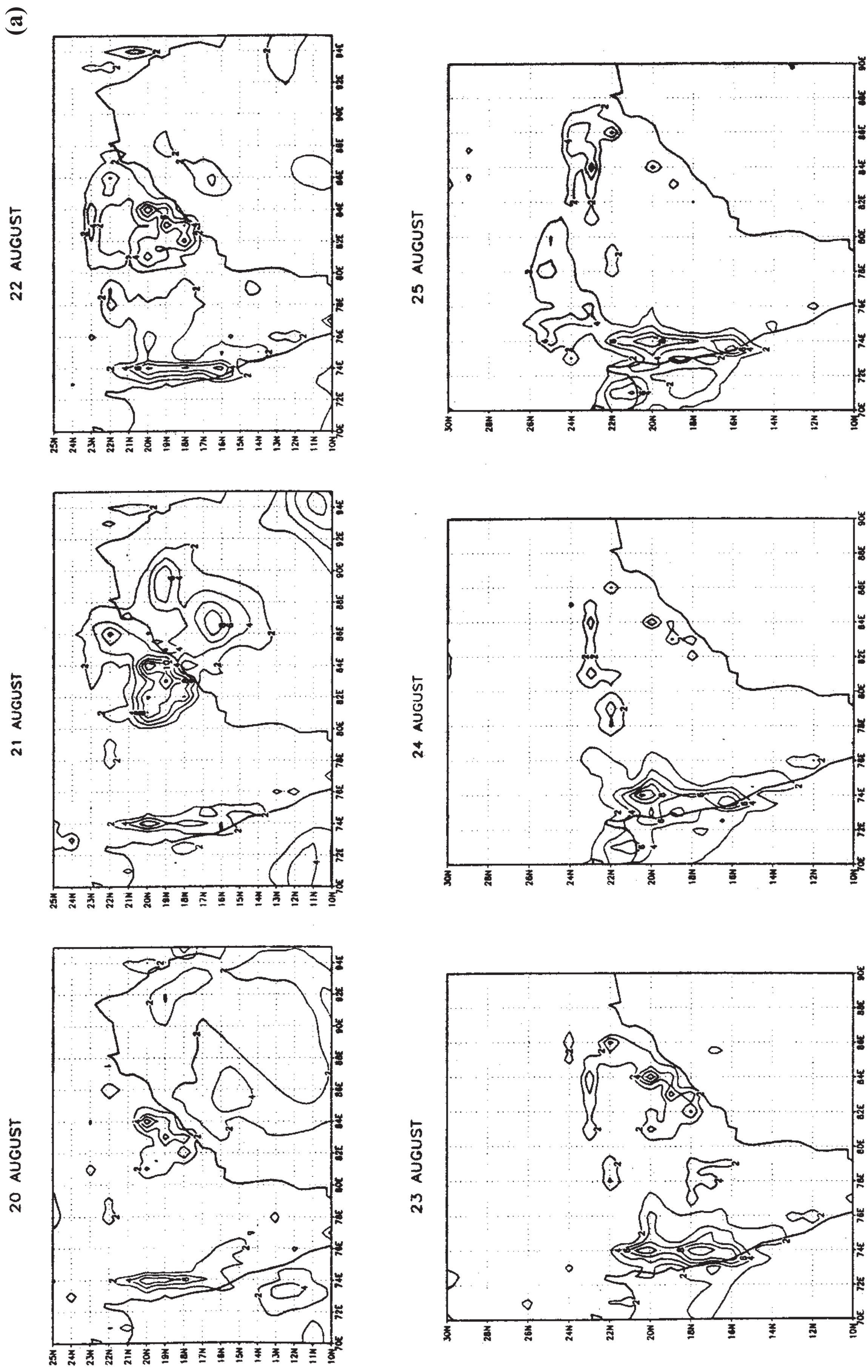


Figure 3(a). *(Continued)*

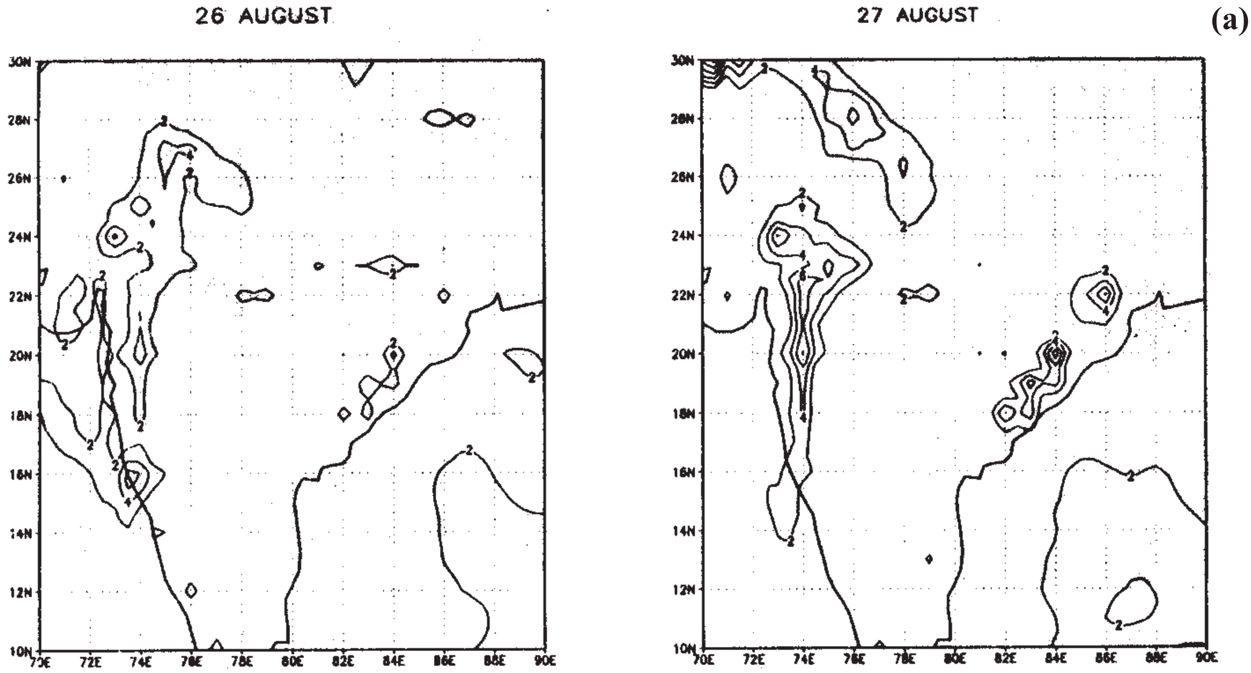


Figure 3(a). (*Continued*)

16 sigma levels are defined in the boundary layer. The 16 sigma levels are 1.0, 0.99, 0.95, 0.90, 0.85, 0.80, 0.75, 0.65, 0.55, 0.45, 0.35, 0.275, 0.225, 0.175, 0.125 and 0.05.

3.1 *Model domain and topography*

The analysis field at the resolution 1° × 1° latitude/longitude from IMD's operational forecasting system is utilized to specify the initial condition. The output from the operational model is interpolated at FGM resolution to specify the initial fields. The inner fine mesh domain (grid 81 × 81) of the model is from equator to 40°N in north-south direction and 60° to 100°E in the east-west direction. The outer course grid model domain is from latitude 30°S to 60°N and longitude 0° to 150°E. The time step of the model is 450 sec.

Model topography is obtained from the USA navy ten minutes global topography data at 0.5° latitude/longitude horizontal resolution and is smoothened by a nine point smoother to prevent instability due to steep gradient of terrain. Obviously mountains are higher and steeper in the FGM domain than in the CGM domain. The peak of the Western Ghat is 750 m in the CGM and 850 m in the FGM.

3.2 *Boundary conditions*

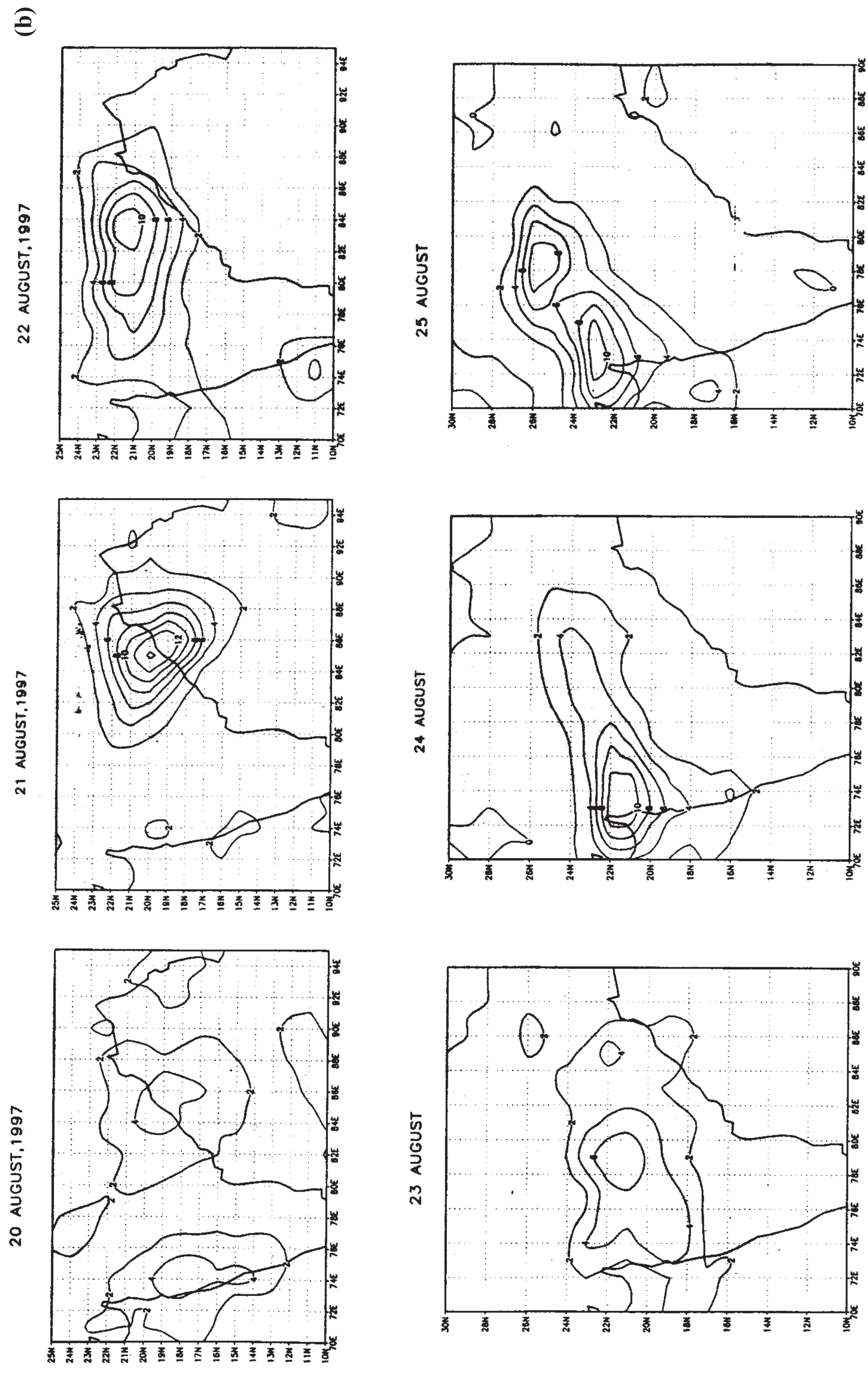
The lateral boundary condition of hydrostatic limited area model remains an unsolved problem. Over the years a number of pragmatic methods have been developed and applied for short range forecasting. An excellent review of these methods can be found in Devis (1983). In the grid nesting approach a much larger domain is also modeled using a coarser resolution. Evolving fields of this CGM are then used to determine the lateral boundary condition for the FGM domain (Kallberg and Gibson 1977). The future value of the prognostic variables at the boundary are obtained from CGM forecast. The lateral boundary conditions of the FGM model are derived from the operational model run and updated every 12 hours. If at any time t, the model forecast X_f and externally specified value X_s, where X is any prognostic variable then the following expression is used to give the merge forecast:

$$X = (1 - \alpha)X_f + \alpha X_s,$$

where α is the weighting factor; α is defined as a quadratic function of the minimum distance from lateral boundary. The merging is done over six grid points at the boundaries of both domains. Also, for consistency, topographic heights at the lateral boundaries of the FGM are specified to be the same as those in the CGM domain. At the model top and bottom the boundary condition for $\dot{\sigma}$ is zero.

4. Synoptic conditions and comparison of forecast rainfall

During the active monsoon period a low pressure area often develops over the Bay of Bengal and



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(b)

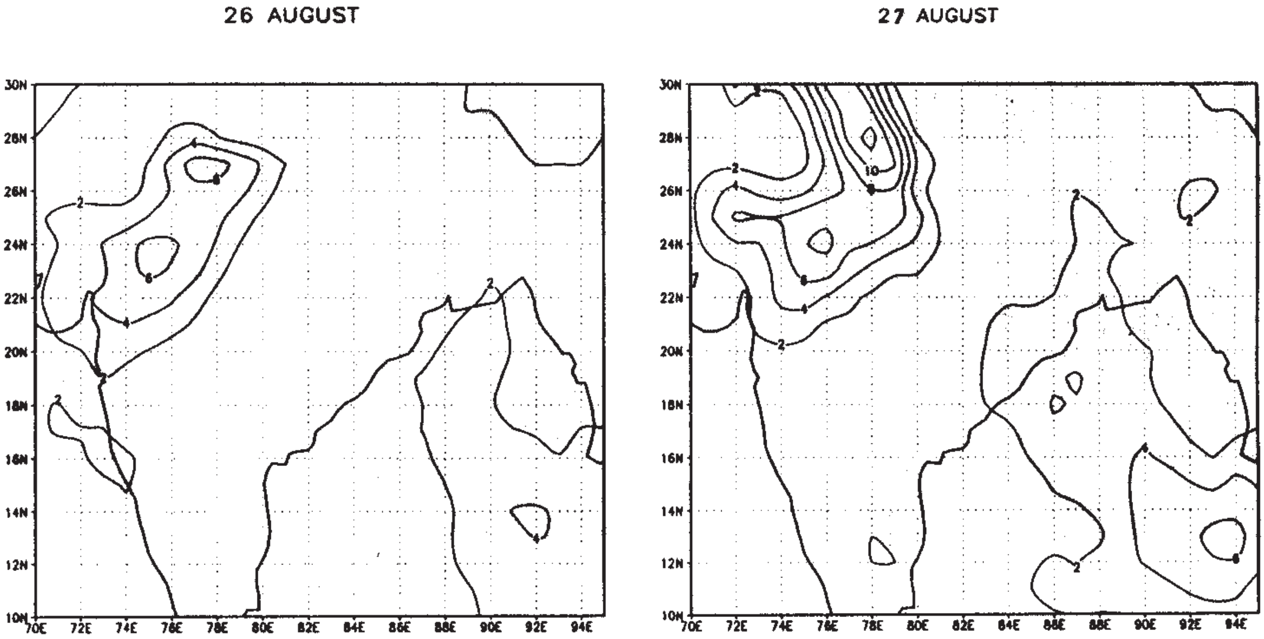


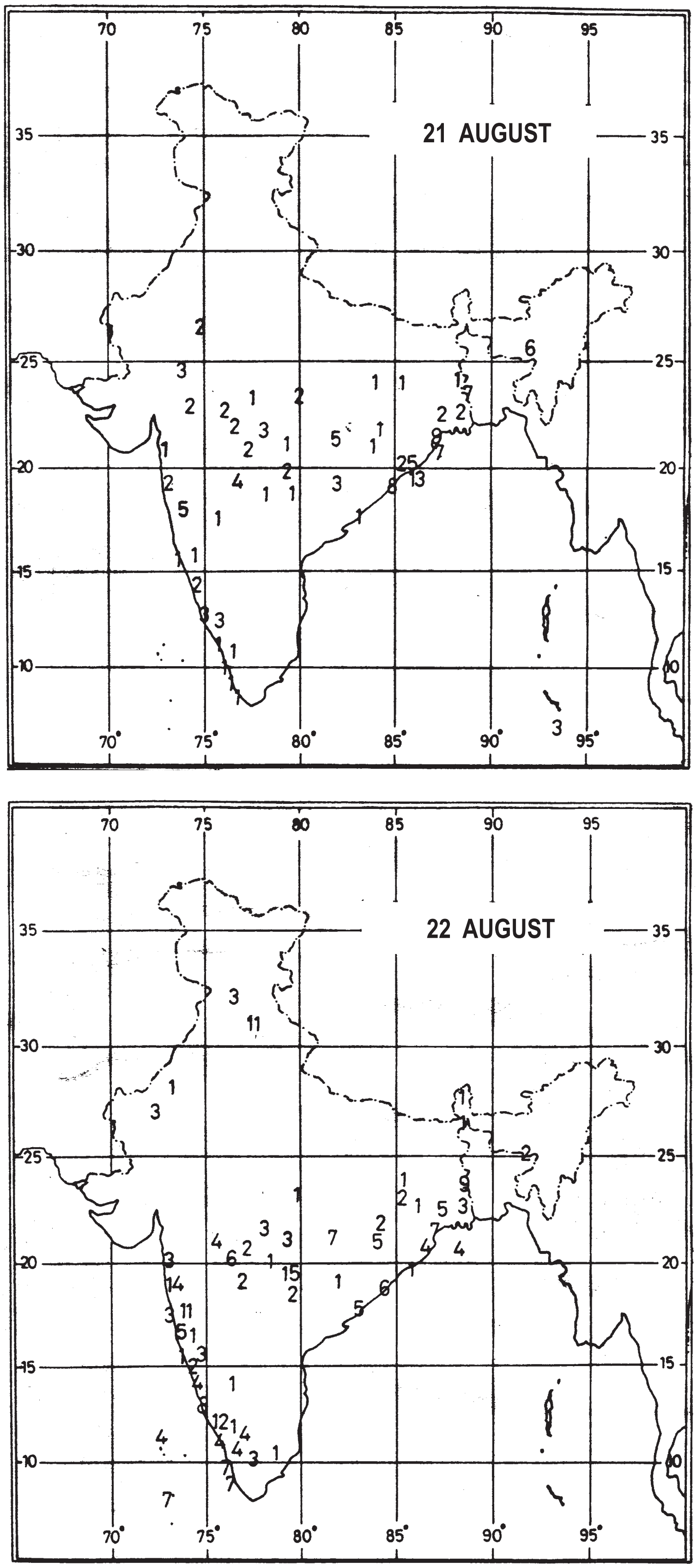
Figure 3(b). (*Continued*)

intensifies into monsoon depression giving rise to heavy rainfall over many parts of India. Here we compare and discuss the results for three distinct cases of monsoon depression and a case of cyclonic storm based on the mesoscale model forecast and compare it to the corresponding coarser grid forecast. In the comparison the results of the mesoscale model and the coarse grid model are referred to as (0.5×0.5) and (1×1) respectively. The rainfall amount referred to in the discussion indicates 24 hours accumulated rainfall. The synoptic conditions described are based on the RSMC (Regional Specialized Meteorological Center) report of the India Meteorological Department. Meteorological subdivisions of India used for describing synoptic conditions and associated realized rainfall are shown in figure 1.

4.1 *Case I: 3rd – 5th August, 1997*

A well-marked low pressure area formed over the north Bay of Bengal on the morning of 4th August 1997 and concentrated into a depression in the afternoon of the same day. Moving in a west-north-westerly direction, it further intensified into a deep depression and lay centered near latitude 21°N/longitude 85°E on the morning of 5th August 1997. On 3rd August no significant rainfall activity was reported from Orissa (such as Balasore and Bhubaneswar 0 mm each, Chandbali 1 m etc.). Rainfall activity started over Orissa, Konkan Goa, and Madhya Maharashtra on 4th August when the system intensified into a deep depression. 24 hours rainfall in cm based on forecast (0.5×0.5) and (1×1) ended at 00 UTC during 3rd – 5th August, 1997 is shown in figure 2(a,b) respectively. The 24 hours rainfall in cm ending at 03 UTC on 4th and 5th August reported by land raingauge stations is shown in figure 2(c). The rainfall maxima of the order of 6 cm (24 hours accumulated) is captured by the model over the north Bay of Bengal in association with the formation of the well marked low pressure area on 3rd August. On 4th August when the system was intensifying into a depression model could produce an increased rainfall amount (maximum 8 cm). In the forecast (0.5×0.5) another belt of mesoscale convective rainfall pocket is indicated over Orissa. On 5th August when the system intensified into a deep depression and moved northwestward the mesoscale activity became more organized and extended further northwestward. Along the Western Ghats of India increased rainfall activity is noticed in the forecast field. These features are in well agreement with the observed rainfall (figure 2(c)). In the corresponding forecast (1×1) the rainfall extends over a much larger area zonally and does not exhibit organization of convection around the monsoon depression. The forecast rainfall (heaviest 12 cm) on 3rd August is higher than that observed when the system was only a well-marked low pressure area. In forecasts of the subsequent two days when the system was intensifying there has been a reduction in the forecast rainfall. Thus a comparison reveals that rainfall distribution produced by the finer resolution model is more realistic.

(c)



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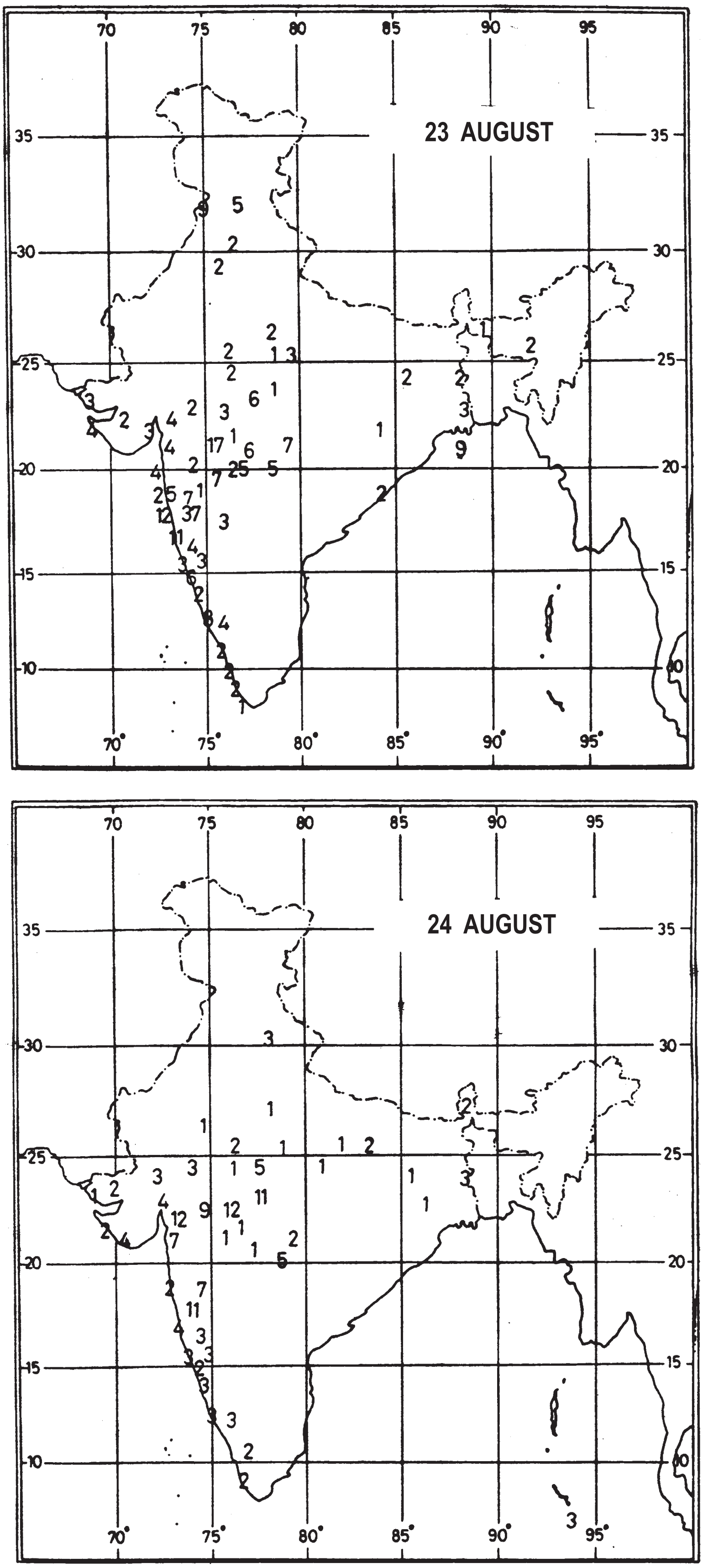

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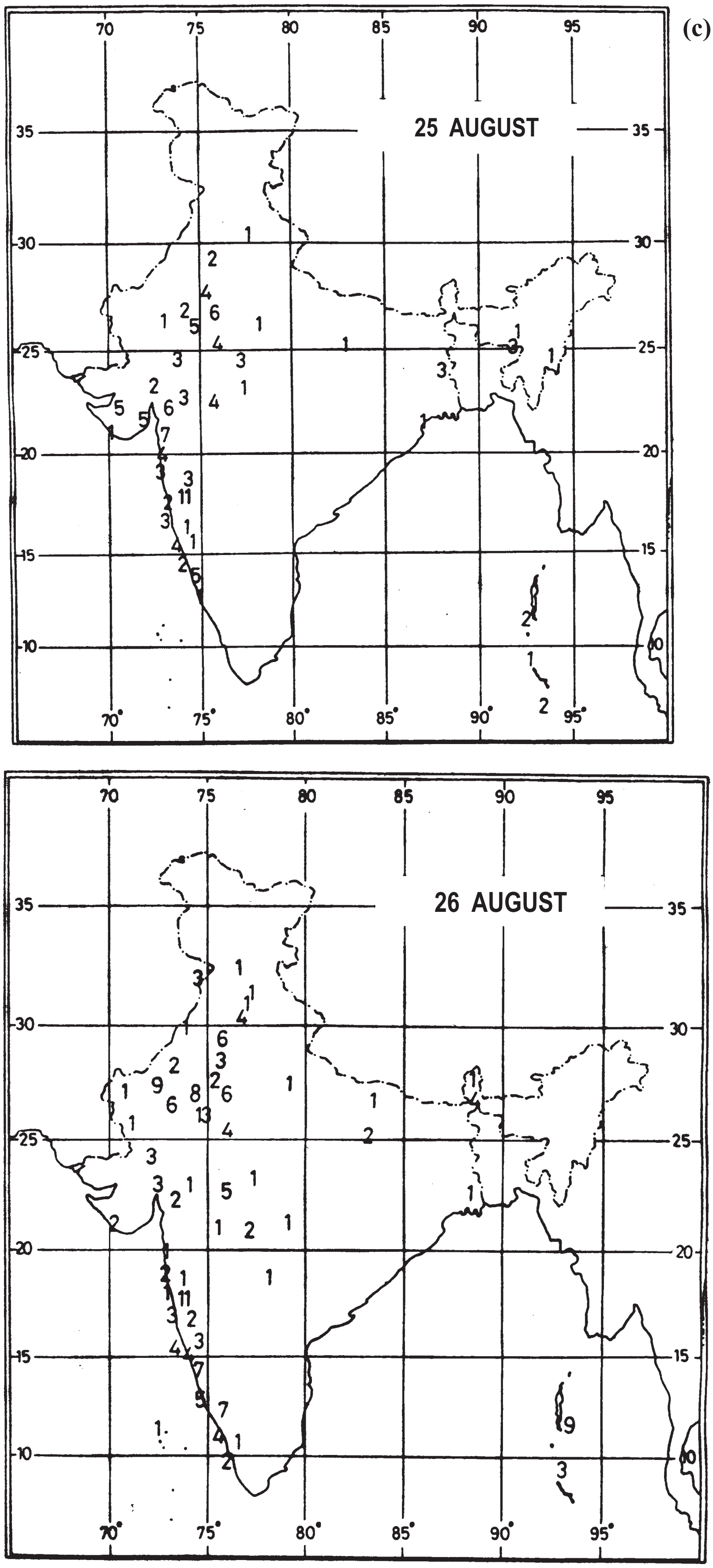

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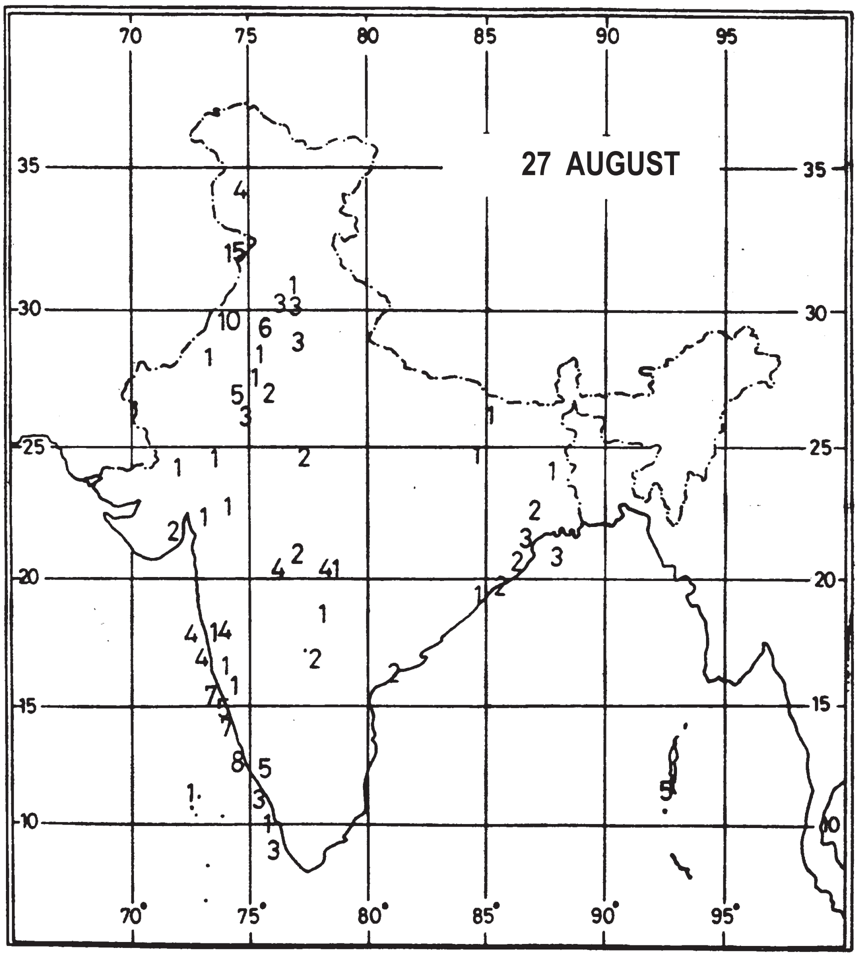


Figure 3. **(a)** 24 hours forecast (0.5 × 0.5) rainfall in cm ending at 00 UTC during 20th – 27th August 1997; **(b)** same as (a) except for forecast (1 × 1) and; **(c)** 24 hours rainfall observations (cm) from land raingauge stations ending at 03 UTC of 21st – 27th August.

4.2 *Case II: 20th – 27th August, 1997*

During 18th–19th August, 1997 a well marked low pressure area lay over the north-west Bay of Bengal off Orissa coast. The system intensified into a depression on 20th August morning and crossed north Orissa coast in the afternoon. Subsequently the system further intensified and on 21st August at 00 UTC lay as deep depression over Orissa. Thereafter the system gradually moved west-north-westwards across north Madhya Pradesh and was located near Jaipur in Rajasthan on the morning of 25th August, 1997. Later it dissipated over Punjab and adjoining Pakistan on the evening of 27th August, 1997. Under the influence of this system the monsoon strengthened over most parts of India. Widespread rainfall with scattered heavy rainfall occurred over Orissa, Madhya Pradesh, Vidarbha, Maharashtra, Gujarat, Rajasthan and west Uttar Pradesh. 24 hours rainfall in cm based on forecast (0.5 × 0.5) and (1 × 1) ended at 00 UTC of 20th – 27th August, 1997 is shown in figure 3(a, b) respectively. The 24 hours rainfall in cm ending at 03 UTC of 21st – 27th August reported by land raingauge stations is shown in figure 3(c). The 24 hours forecast (0.5 × 0.5) rainfall exhibits organization of mesoscale convective precipitation around the depression centre. On 20th August two belts of rainfall maxima, one over the north Bay (4 cm) and another over Orissa coast (2–4 cm) are simulated by the model. On 21st August when the depression intensified into a deep depression a robust organization of convection around the monsoon depression (8 cm over the Bay of Bengal and 10 cm over Orissa coast) is noticed. On 22nd August when the system moved over land, rainfall over the Bay significantly decreased, while convective activity over Orissa and also over the west coast of India continued. Scattered heavy to very heavy rainfall as observed over coastal stations of Orissa (figure 3(c)) (like Bhubaneswar 25 cm, Puri 13 cm etc. on 21st August) are consistent with the model forecast. During 23rd – 27th August, as the depression moved west-north-westward, the

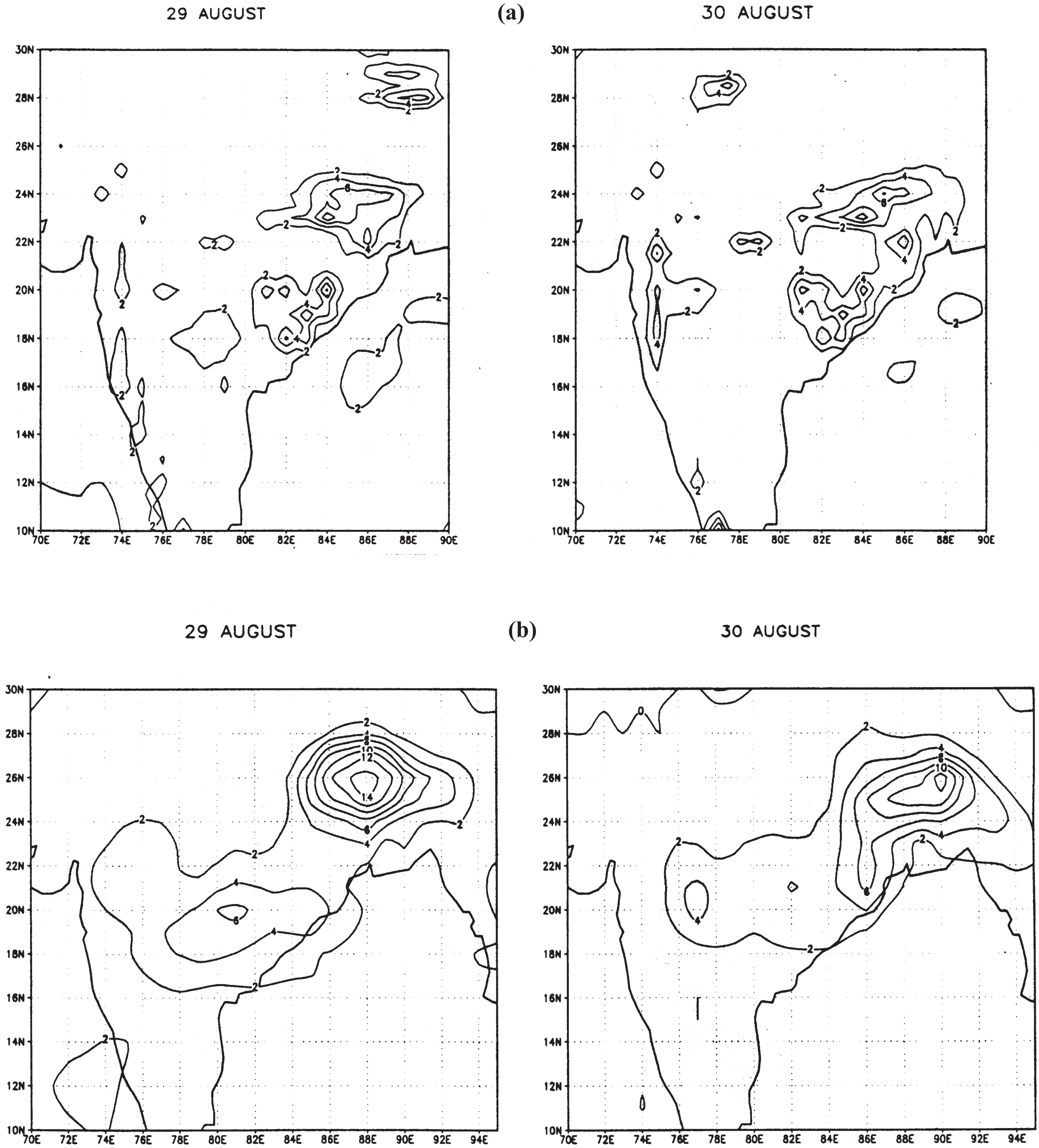
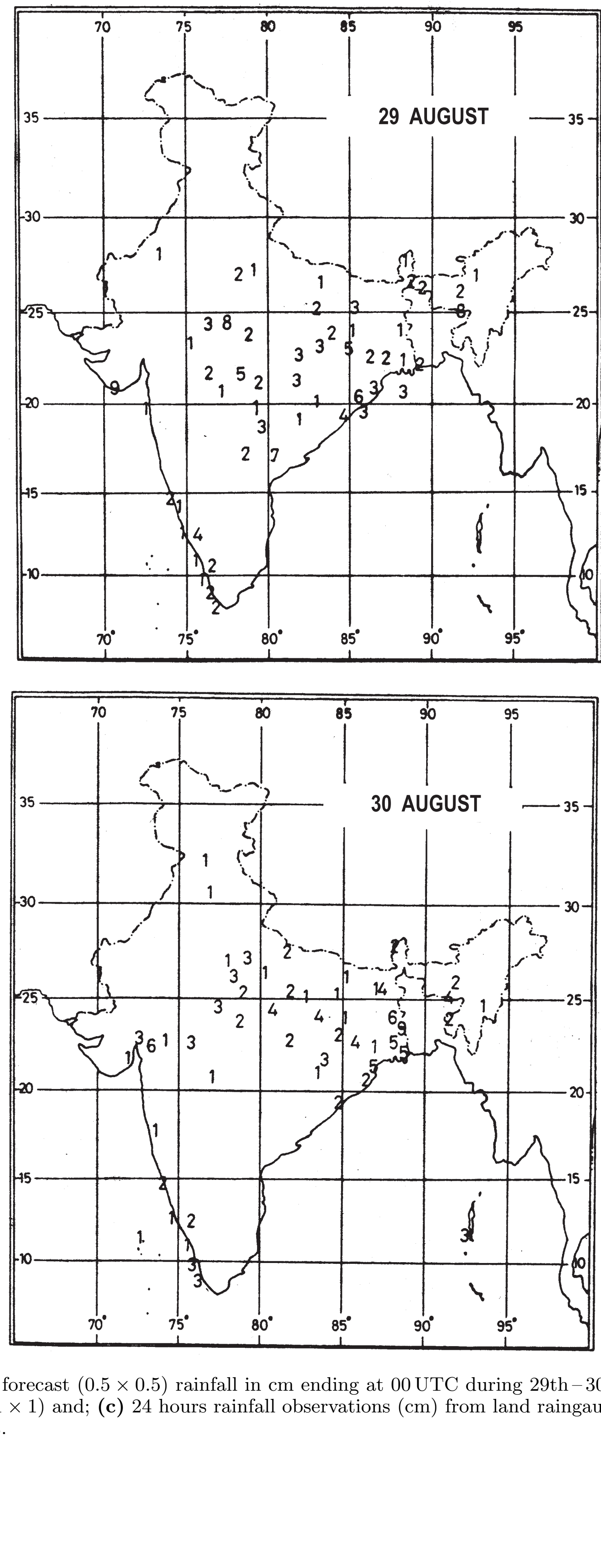


Figure 4(a, b). (*Continued*)

location of mesoscale rainfall organizations was found to shift along with the depression. Along the west coast of India the orographic convective rainfall belt is well captured by the model and is consistent with the observed heavy rainfall (such as Mumbai 14 cm, Alibagh 7 cm, Ratnagiri and Dahanu 5 cm each of 22nd August; Mumbai 25 cm, Harnai 12 cm, Ratnagiri 11 cm etc. of 23rd August). In the model at the coarser grid resolution (figure 3(b)) the rainfall pattern associated with monsoon depression was much broader than observed. Enhanced orographic rainfall over the west coast of India and mesoscale convection around the monsoon depression have been simulated much better by the finer resolution model.



(c)

Figure 4. **(a)** 24 hours forecast (0.5 × 0.5) rainfall in cm ending at 00 UTC during 29th – 30th August 1997; **(b)** same as (a) except for forecast (1 × 1) and; **(c)** 24 hours rainfall observations (cm) from land raingauge stations ending at 03 UTC of 29th and 30th August.

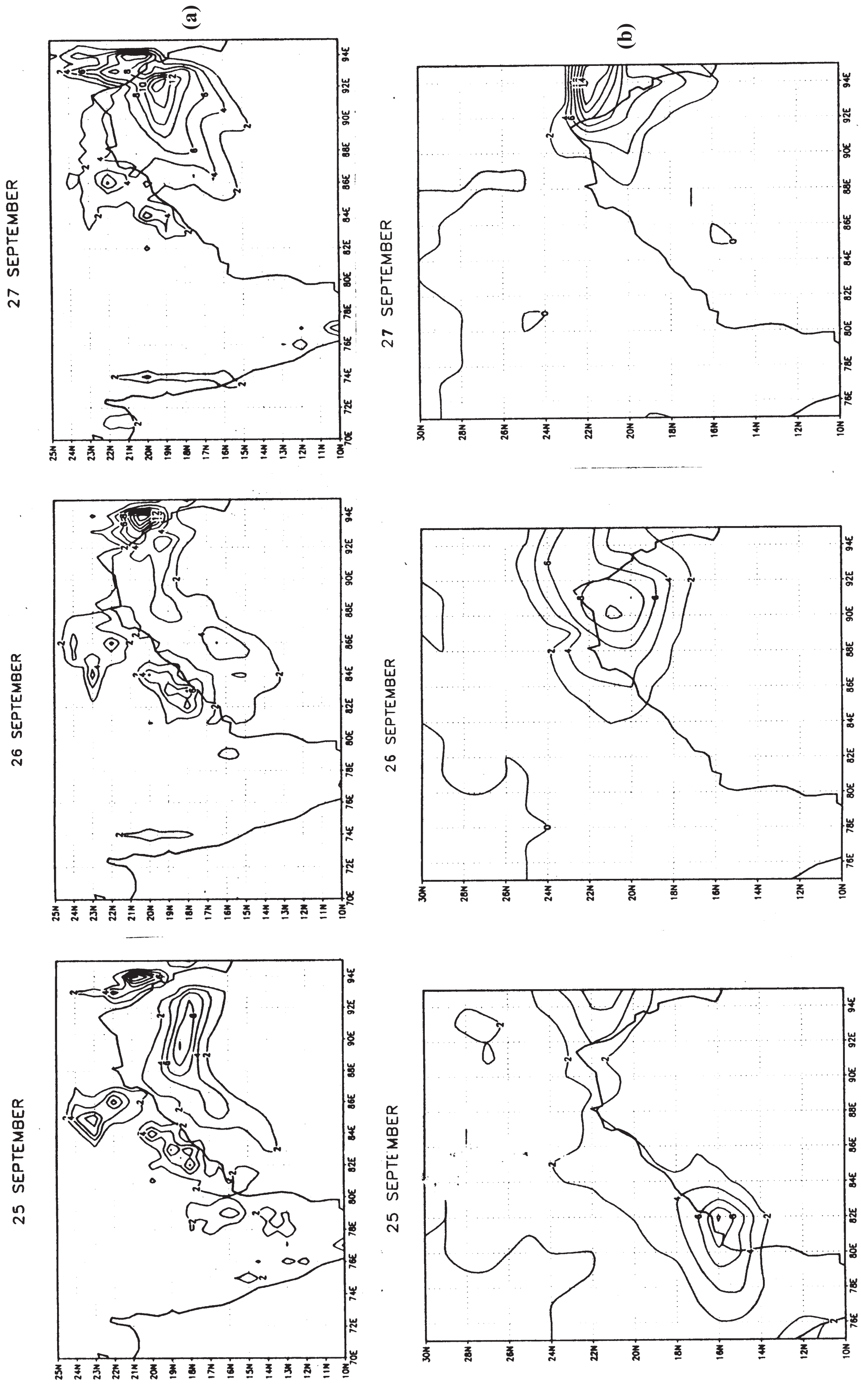


Figure 5(a, b). (*Continued*)

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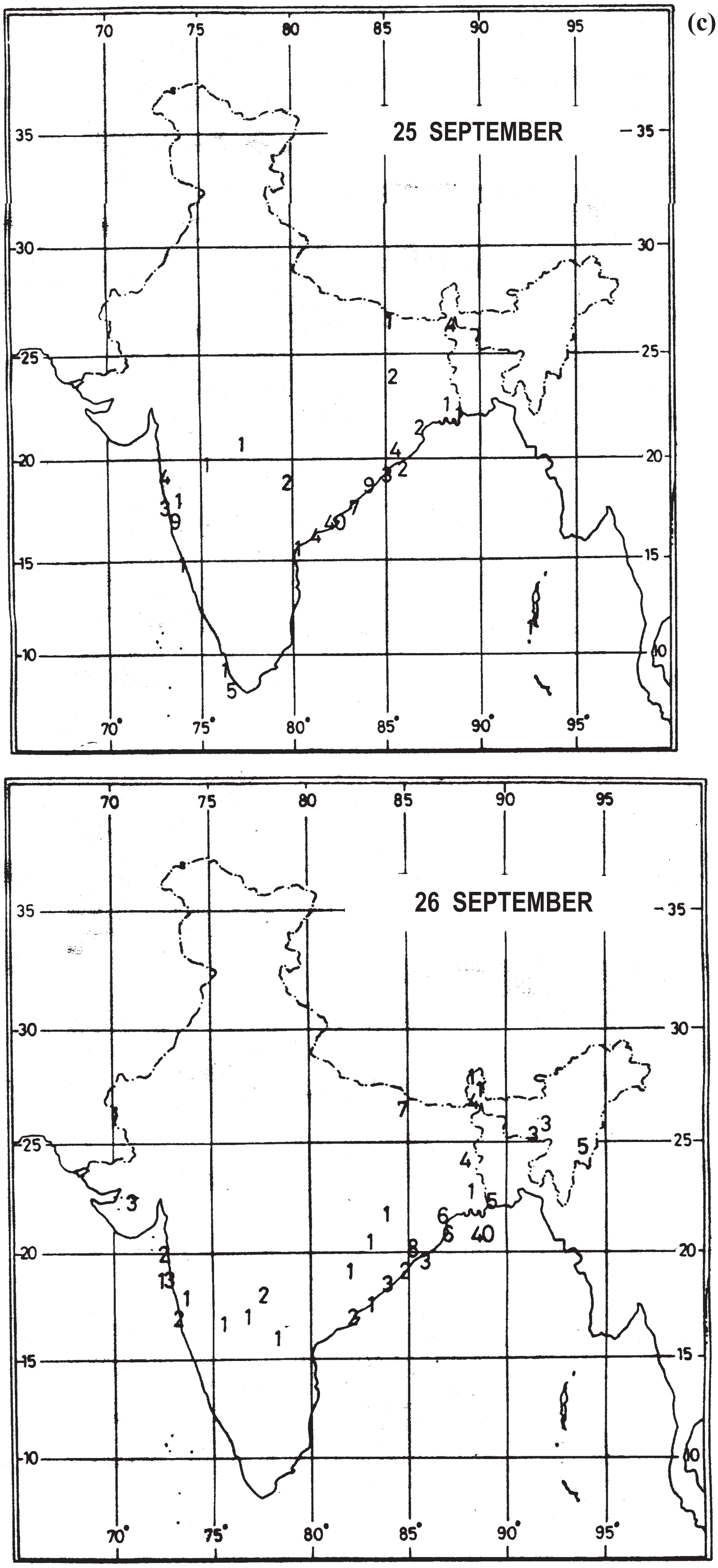

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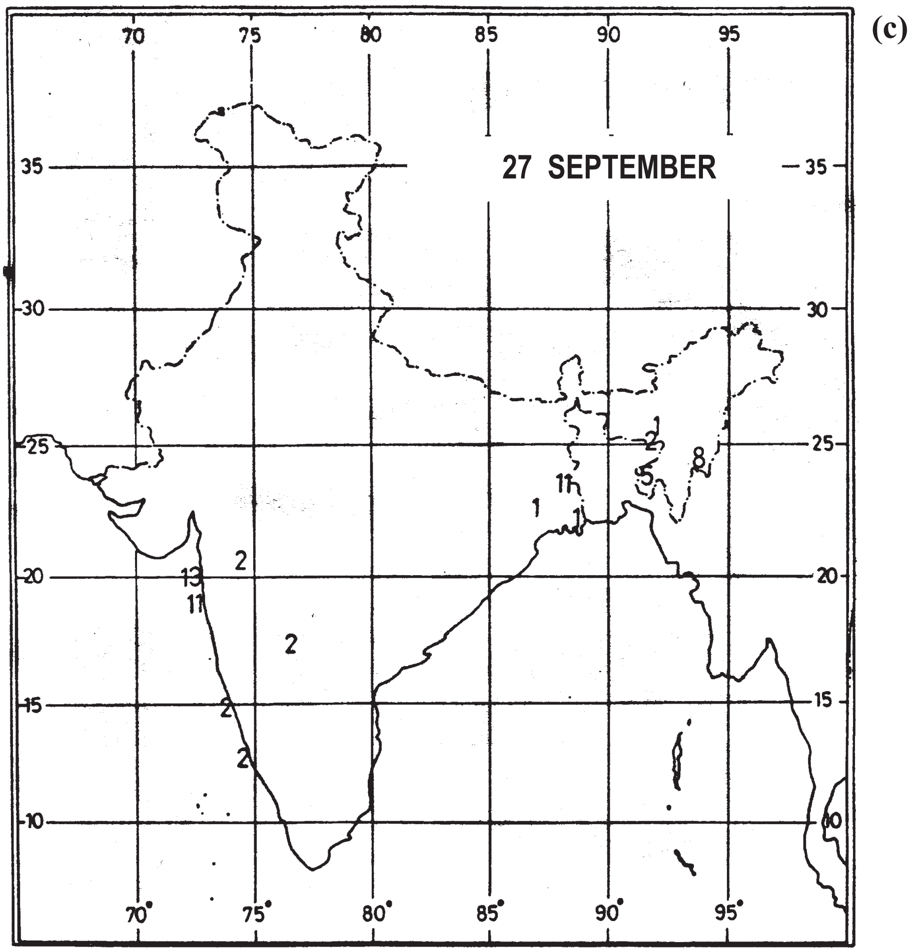

Figure 5. **(a)** 24 hours forecast (0.5 × 0.5) rainfall in cm ending at 00 UTC during 25th – 27th September 1997; **(b)** same as (a) except for forecast (1 × 1) and; **(c)** 24 hours rainfall observations (cm) from land raingauge stations ending at 03 UTC of 25th to 27th September.

4.3 *Case III: 28th – 30th August, 1997*

After the deep depression of 20th – 27th August, 1997, another depression formed over the northwest Bay of Bengal off Orissa coast on the morning of 28th August and was centred near latitude 19°N/longitude 87°E. Moving in a northwesterly direction, it crossed the Orissa coast in the afternoon of the same day. Moving further in a nearly northerly direction it moved into Jharkhand-Bihar by the morning of 30th August. Under the influence of this system widespread rainfall with rather heavy falls occurred over Orissa, Gangetic West Bengal, Jharkhand and Bihar. 24 hours forecast (0.5 × 0.5) and (1 × 1) rainfall ending at 00 UTC of 29th and 30th August is shown in figure 4(a, b) respectively. As expected forecast (0.5 × 0.5) rainfall distribution exhibits mesoscale organization around the monsoon depression. Orographic rainfall as predicted over north Konkan and adjoining Gujarat region is not reflected in the forecast (1 × 1). The rainfall distribution which shows two convective belts, one over Orissa and other over Jharkhand and Bihar in the finer resolution forecast is consistent with the observed rainfall distribution (figure 4c). The comparison reveals that the finer resolution forecast is closer to the observations.

4.4 *Case IV: 25th – 28th September, 1997*

A depression formed over the west central Bay of Bengal on 23rd September. It intensified into a cyclonic storm on the evening of 24th September. Moving in a northerly direction it crossed Bangladesh coast as a severe cyclonic storm on the night of 26th September and was located as cyclonic storm over land on the morning of 27th September and dissipated by the evening.

A significant feature of this cyclone is that the system formed close to south Andhra Pradesh coast and moved along the coast and maintained its intensity as cyclonic storm up to 26th September. It turned into a severe cyclonic storm at the time of crossing the coast.

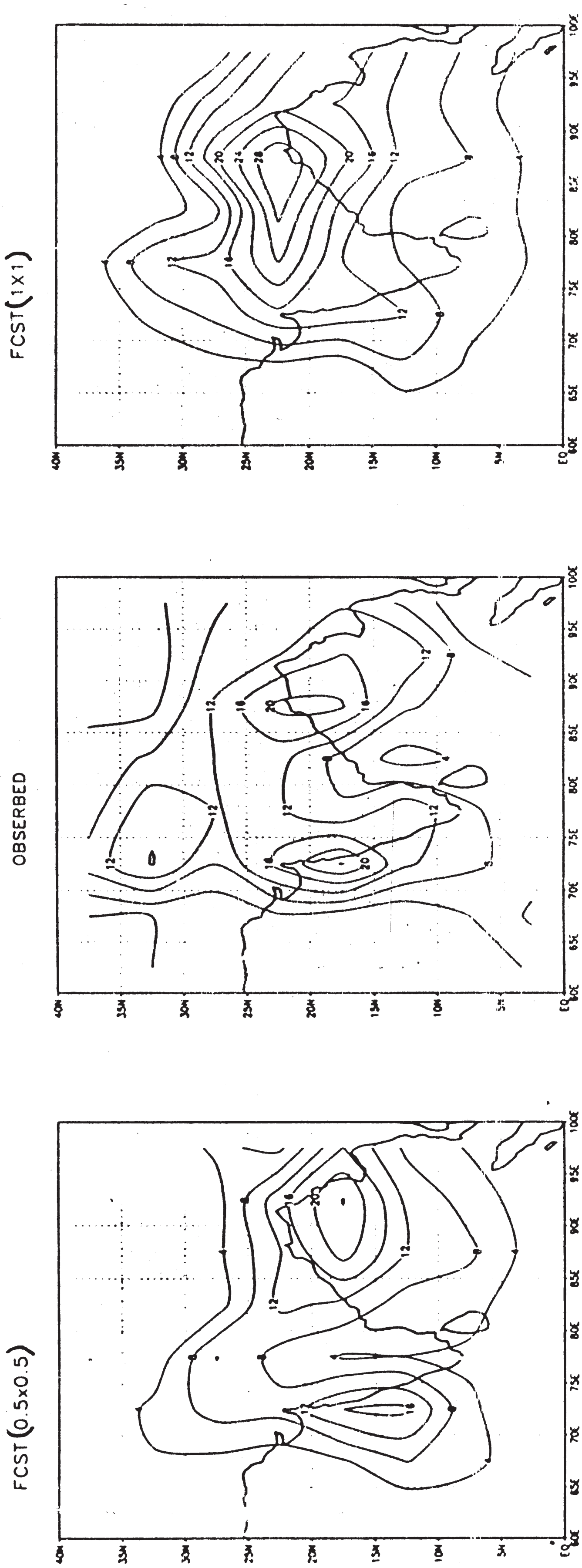

Figure 6. A comparison of 24 hours mean rainfall in cm of August 1997 among forecast (0.5 × 0.5), observed and forecast (1 × 1).

Figure 5(a) shows 24 hours forecast (0.5×0.5) rainfall distribution ending at 00 UTC of 25th, 26th and 27th September. On 25th when the cyclonic storm lay centred near latitude 17.5°N/longitude 83.5°E, three active convective pockets are noticed (maximum 8 cm to the east) around the cyclone center. Corresponding forecast (1×1) and observed rainfall are shown in figure 5(b and c) respectively. Though both models were able to capture the northward shift of the rainfall belt as the system moved northwards, in the coarser grid forecast the shift was faster and the rainfall pattern was much broader. The distribution of rainfall in the finer resolution was closer to the observations.

4.5 *Verification of forecast rainfall*

Observations with a resolution that is high enough to check the performance of (0.5×0.5) forecast are not available at present. The only source of data available to us on rainfall over the sea is the INSAT (Indian Geostationary Satellite) derived precipitation (24 hours accumulated). This is available on a resolution of $2.5° \times 2.5°$ latitude/longitude (currently available at $1° \times 1°$ latitude/longitude) and is based on the algorithm described by Arkin *et al* (1989). The satellite data together with raingauge data from land have been used to produce a dataset with uniform grid resolution of $2.5° \times 2.5°$ latitude/longitude. Similar grids have been generated for the finer resolution and coarse resolution model predictors. These datasets have been used to compare mean rainfall for August 1997. Distribution of rainfall as seen in the three datasets is shown in figure 6. The comparison reveals that orographic convective rainfall along the west coast of India is captured by the finer resolution model, but is not by the lower resolution model. The observed rainfall is seen in agreement with the finer resolution forecast. The coarser model forecast rainfall is higher than the observed.

5. Conclusions

Monsoon rainfall forecasting has been one of the difficult areas in numerical weather prediction. This is due to the complex issues which involve: impact of orography, treatment of synoptic scale low pressure systems, mesoscale convective systems and lack of good quality data over the oceans. For the prediction of mesoscale convective rainfall it is necessary to have a dense and good quality observational network. Such data network is not available at present. Despite the lack of mesoscale observational network the present study reveals that the model at the increased resolution could capture the mesoscale convective organizations associated with monsoon depression. These features are not seen at the operational run at lower resolution where the rainfall distributions are much broader and tend to be more zonal. The major limitation of the operational model is that it fails to capture orographic rainfall along the Western Ghats of India. The present study clearly shows that with the enhanced terrain height at the increased horizontal resolution, the model could capture the heavy rainfall belt along the Western Ghats.

The mesoscale rainfall prediction skill (particularly meso-β and meso-γ) in the tropics is still far from a satisfactory solution, particularly for forecast beyond 24 hours (preferably up to 72 hours). There is scope for further development of work from the use of very high resolution non-hydrostatic models (such as MM-5). But most desirable would be to develop a mesoscale data assimilation scheme incorporating various remote sensing data.

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