Meteorol. Atmos. Phys. 76, 223–236 (2001)

Meteorology
and Atmospheric
Physics

India Meteorological Department, Mausam Bhavan, Lodi Road, New Delhi-110003, India

Some characteristics of Limited-Area Model-Precipitation forecast of Indian monsoon and evaluation of associated flow features

S. K. Roy Bhowmik and **K. Prasad**

With 14 Figures

Received May 2, 2000
Revised September 18, 2000

Summary

The Florida State University based Limited-Area Model is in operational use at India Meteorological Department, New Delhi. This paper assesses the performance of the model in temporal and spatial scale to provide 24 hours rainfall forecast over Indian region during south-west monsoon (June to September) and north-east monsoon season (October and November) using three years data (1997–1999). Characteristic features of mean flow pattern produced by the forecast (24 hours) are also examined comparing them with the corresponding analysis fields.

The study demonstrates that performance of the numerical model in predicting precipitation varies with month, geographic location and by synoptic regime. The model, in general, is able to reproduce the spatial pattern of monthly and seasonal rainfall but under-estimates orographic rainfall and over estimates rainfall associated with the monsoon low pressure systems. In October and November when the low pressure belt shifts to the southern latitudes of India, the model is able to capture the heavy rainfall zone confined over south Peninsula. Time series and categorical statistics show that there is a very good correspondence between observed and predicted rainfall.

The other important characteristic features of south west monsoon are well captured by the model and are comparable with the analysis field. But some of the significant deficiencies noticed in the forecast are: higher mean sea-level pressure, particularly over the domain of heat low and relatively weaker lower tropospheric westerlies.

The results of this paper will provide useful input on model performance to operational forecasters and model developers.

1. Introduction

A Limited-Area-Analysis-Forecast System (LAFS) in operational use at India Meteorological Department (IMD), New Delhi consists of real time processing of data received on Global Telecommunication System (GTS), objective analysis by three-dimensional multivariate optimum interpolation scheme and multilayer primitive equation model. The model is an adapted version of the Florida State University Limited-Area Model (LAM). Horizontal resolution of the model is $1^\circ \times 1^\circ$ lat./long. and it has 12 sigma levels in the vertical. The total rainfall in the model comes from the parameterization of cumulus convection, shallow convection and from the deposition of supersaturation. The model includes a modified Kuo's cumulus parameterization scheme, where two dynamical parameters, namely vertically integrated omega field and relative vorticity at 700 hPa are directly involved in the model rainfall calculation over a grid domain. The detailed description of the model is given by Krishnamurti et al. (1989).

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 maximum terrain envelope obtained is 4.8 km. The other features of the model include time dependent lateral boundary conditions and dynamical normal model initialization. The model is run up to 48 hours, twice daily initiated with 00 UTC and 12 UTC observations. Lateral boundary conditions of the model are derived from the global spectral model (T-80) run of the National Center for Medium Range Weather Forecasting (NCMRWF), New Delhi and are updated every 12 hours. The first guess field for objective analysis is also provided by NCMRWF-forecast.

There remains a pressing need in operational practices to provide quantitative precipitation forecast with greater accuracy. Though rapid progress in the field of numerical weather prediction has been achieved during recent years, the progress in the rainfall prediction is still slow. Before one goes for further improvement of a numerical model, an investigation on the performance statistics of the model on temporal and spatial scale is a prerequisite. Moreover, forecasters can improve quantitative precipitation forecast skill through their knowledge of performance statistics of the operational numerical models. Knowledge of temporal and spatial variation in the performance of the numerical model should help understand some of the limitation of model's quantitative rainfall forecast and may help the forecasters to provide more accurate quantitative forecast. Because of these two considerations, efforts have been made by several researchers to study performance statistics of some operational models. Performance statistics for the precipitation forecast of the NMC-operational model have been demonstrated by Jensenius (1990), Junker et al. (1989), Junker and Hoke (1990), Junker et al. (1992). The rainfall performance statistics of BMRC-operational model is made by Ebert and McBride (1997). An intercomparison of the characteristic features of the Indian summer monsoon 1995, produced by some of the operational centers such as ECMWF, UKMO and NCMRWF was made by Basu et al. (1999). But such a study for the operational model of IMD is not available. In this paper performance statistics of the operational model of IMD have been examined.

During the south-west monsoon season (June–September), the northern and central parts of Indian sub-continent often receive widespread heavy rainfall under the influence of synoptic scale low pressure systems and also in association with meso-scale systems and processes. The north-east monsoon season (October–November) is another period when heavy rainfall occurs over the southern Peninsula of India in association with the shifting of low pressure belt to the south-west Bay of Bengal and neighborhood. The aim of this study is to assess the 24 hours rainfall prediction skill of IMD's operational model over Indian region during these rainy seasons. The aim of this study is also to determine how well the characteristic flow features can be reproduced over Indian region by the operational model, comparing and verifying them with reference to corresponding observations and analysis. This performance statistics will provide useful input on model performance at spatial and temporal scales to operational forecasters and model developers.

In Sect. 2, data and methodology adopted for this study are discussed. In Sect. 3, we evaluate rainfall prediction skill of the model. Section 4 contains comparison of circulation features while vertical profiles are compared in Sect. 5. Finally Sect. 6 summarizes and concludes.

2. Data and methodology

As adequate land observations are available over the country (India), raingauge observations received on GTS (Global Telecommunication System) as well as DRMS (District-wise Rainfall Monitoring Scheme) network of India Meteorological Department (IMD) are utilized as observed data set. In order to cover the data gaps over the sea area, the rainfall data-set is supplemented by INSAT derived precipitation estimates. The data from the Indian Geostationary Satellite (INSAT) are derived on the grid resolution $2.5^\circ \times 2.5^\circ$ lat./long. following the algorithm described by Arkin et al. (1989). The approach is identical with one which is used to obtain such estimates for the GOES satellite. This is the only source of data available to us at present for verification of rainfall over the sea. Since model rainfall is at the resolution of $1^\circ \times 1^\circ$ lat./long., to obtain a comparable data-set both forecast and observed data are converted into uniform grid resolution of $5^\circ \times 5^\circ$ lat./long. computing areal average rainfall for the grid box. Selection of this resolution is due to the consideration to accommodate more number of observations for a reasonable representation of grid box. The verification data set of this study covers the area between latitude 0 degree north to 40 degree north and longitude 60 degree east to 100 degree east.

The south west monsoon over the Indian subcontinent has three distinct phases (like onset phase during June, active cycle during July–August and withdrawal phase during September). The rainfall exhibits interseasonal variability. Again, October is the onset phase of north-east monsoon and November is the active phase. Because of these considerations it is appropriare to make a quantitative assessment of precipitation prediction skill of the model on spatial and temporal scales. In this paper, we present monthly verification maps based on observed, forecast and their difference (mean error) for each month from June to November. The validation of data is simply the total of daily rainfall analysis corresponding to model forecast. The verification maps are based on the available three years data for the period 1997–1999. We also present the time series of daily space mean rainfall and the spatial correlation coefficient between forecast and observed rainfall amount for the south-west monsoon period of 1997. Computation and comparison of some of the commonly used categorical statistics (Stanski et al., 1989), like bias and threat scores, are also included in this study. A bias score (B) and a threat score (T) are defined as:

B = (F+H)/(M+H),
T = H/(F+M+H),
where,

F = number of false alarm
M = number of missing points
H = number of hits.

In order to assess the ability of the model to capture characteristic flow features of south-west monsoon, mean flow patterns of August, 1997 forecast (24 hours) versus analysis have been compared. Distribution of mean monthly fields as captured in the analysis and forecast on a constant pressure surface are computed for the same domain. The meteorological fields included for the comparison are: mean sea-level pressure and circulation features at a lower and upper tropospheric level each.

In order to examine how well the vertical structure of heavy rainfall belts are reproduced by the model, vertical profiles of some of the parameters like relative humidity, relative vorticity, divergence and vertical velocity over smaller domains of synoptic interest are also compared by taking time averaged area mean over the square box of size 2° × 2° lat./long.

3. Evaluation of precipitation forecasts

3.1 Monthly pattern

We begin with a description of monthly rainfall based on observed, forecast and their difference (mean error). Figure 1 to 6 illustrate monthly verification maps of mean rainfall for June to November, respectively based on data for the years 1997–1999. In the month of June, the observed rainfall distribution shows a north-south

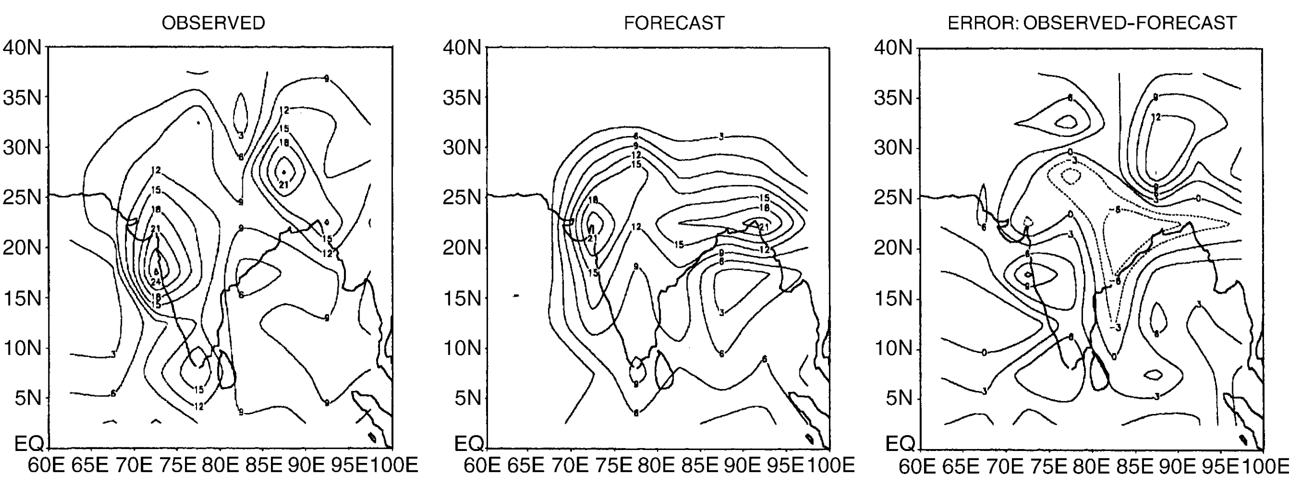

Fig. 1. Comparison of mean rainfall (mm/day) of June between forecast and observed for the data period 1997–1999

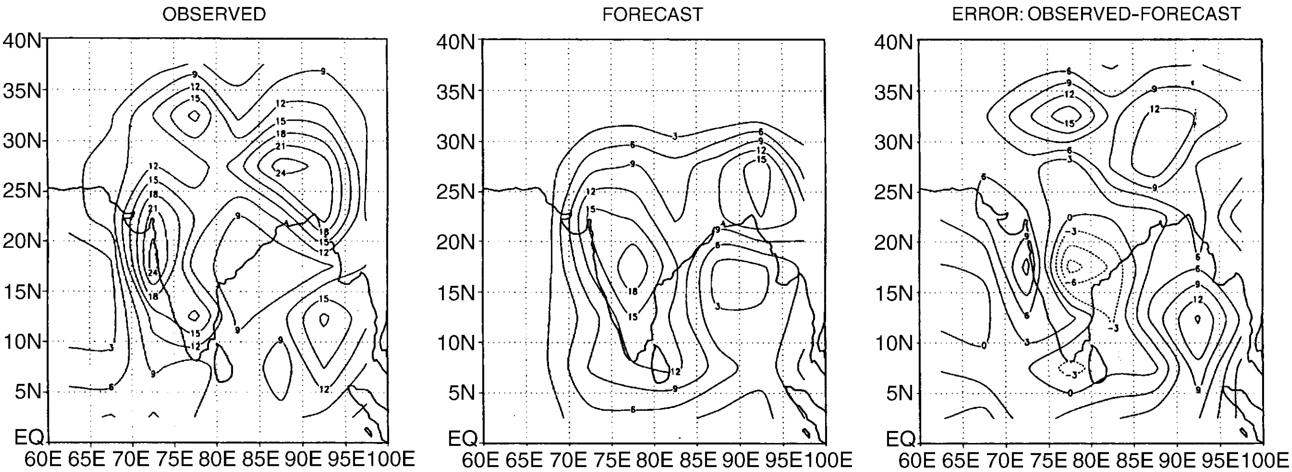

Fig. 2. Same as Fig. 1 for July

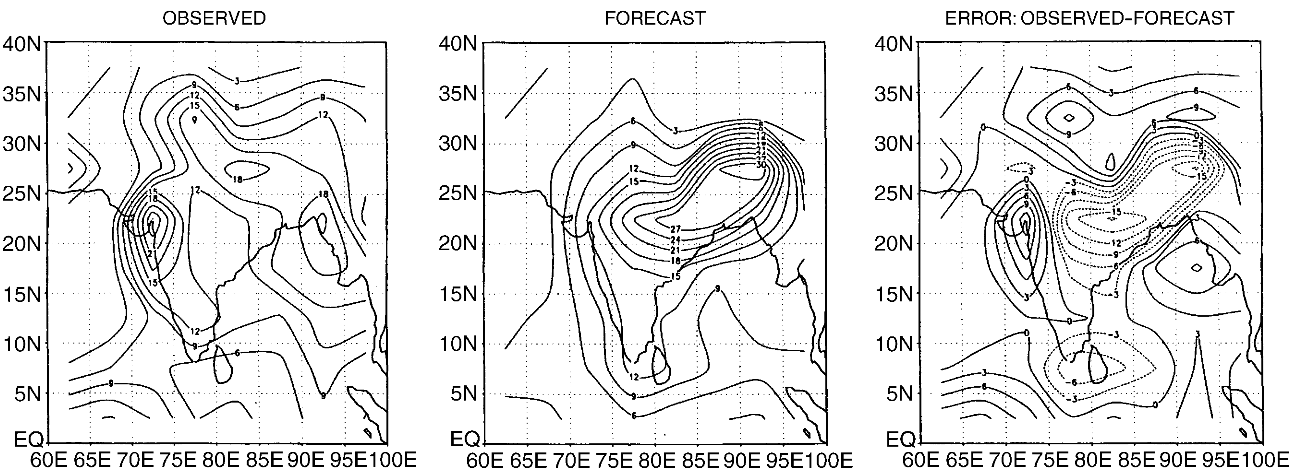

Fig. 3. Same as Fig. 1 for August

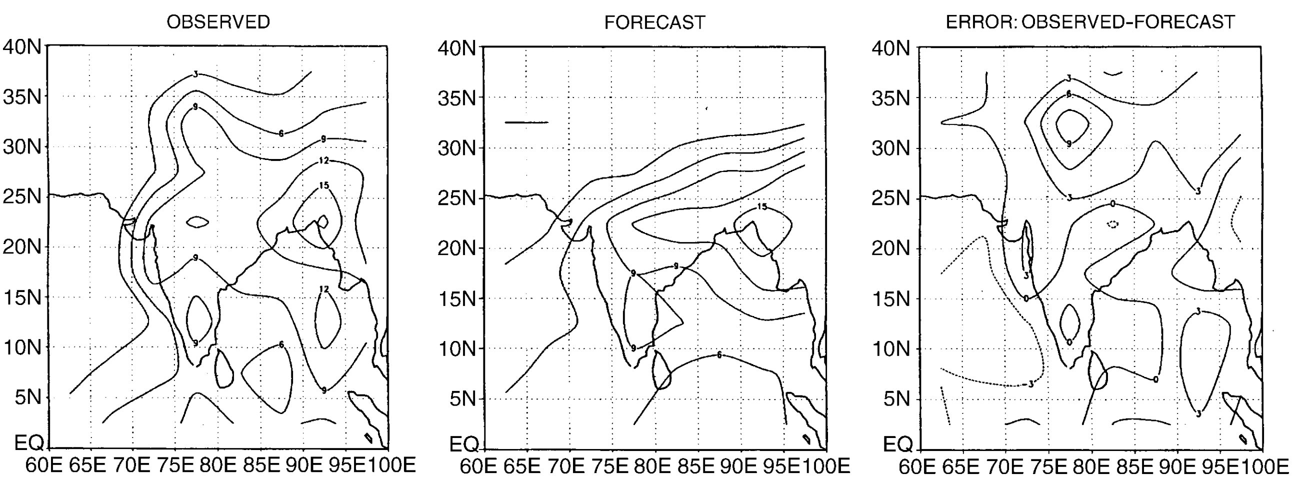

Fig. 4. Same as Fig. 1 for September

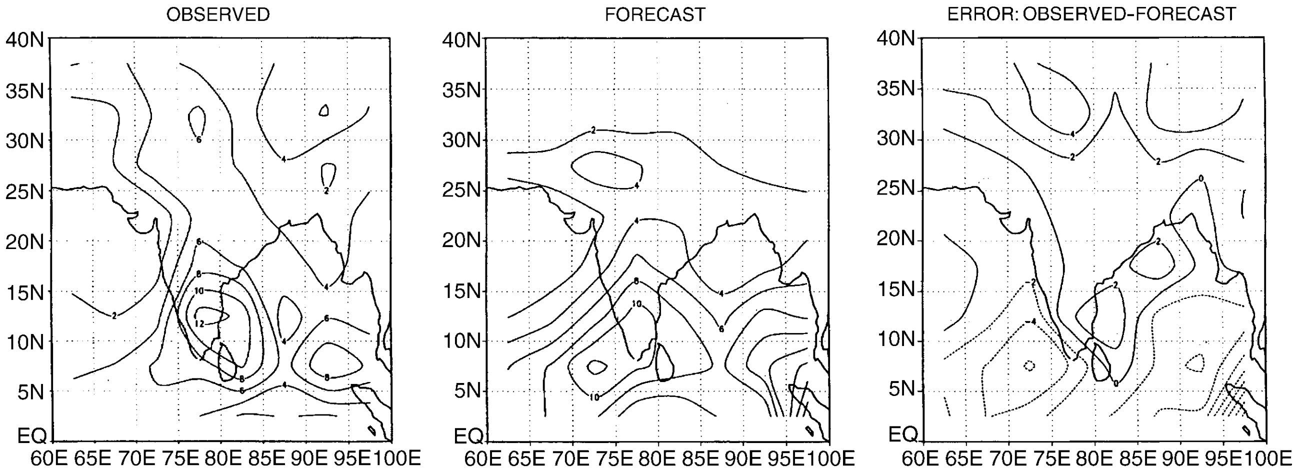

Fig. 5. Same as Fig. 1 for October

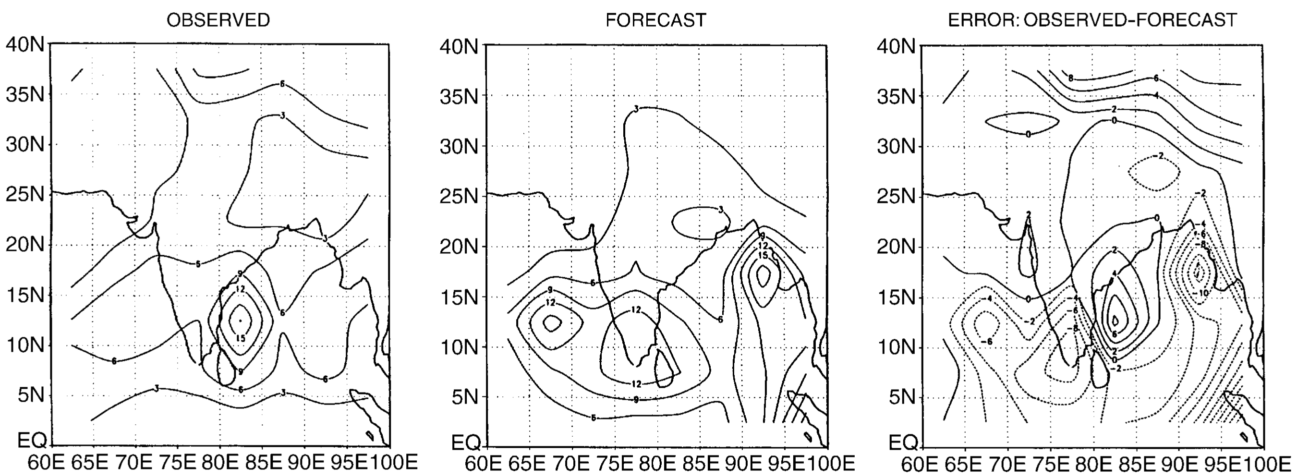

Fig. 6. Same as Fig. 1 for November

oriented belt of heavy rainfall along longitude 74° E between latitude 14° N and 26° N with a peak centered near lat. 18° N/long. 74° E (24 mm/day). Another heavy rainfall pocket is observed over north-east India centered near lat. 27° N/long. 87° E (21 mm/day). The third heavy rainfall pocket (15 mm/day) is observed over the extreme south tip of India near lat. 7° N/long. 76° E. The corresponding forecast mean field could reproduce north-south oriented rainfall over western Ghats of India along longitude 74° E. with peak centered at lat. 21° N/long. 74° E (21 mm/day). The heavy rainfall domain over north east India is captured with the maximum centered near lat. 23° N/long. 91° E with a value of 21 mm/day. A small pocket of heavy rainfall (9 mm/day) is also seen near lat. 7° N/long. 77° E and over the southern tip of India. Mean error indicates over-estimation of rainfall over north-east India by an amount of 6 mm/day and under-estimation of rainfall over the region roughly between longitude 74° E and 76° E and also over the region north of lat. 30° N.

In the month of July observed heavy rainfall peaks are located over Western Ghats of India near lat. 17° N/long. 74° E (24 mm/day), over the region of monsoon trough centered at lat. 27° N/long. 87° E and at lat. 31° N/long. 76° E (15 mm/day). In the forecast pattern, one peak (18 mm/day) is located near lat. 17° N/long. 76° E to the

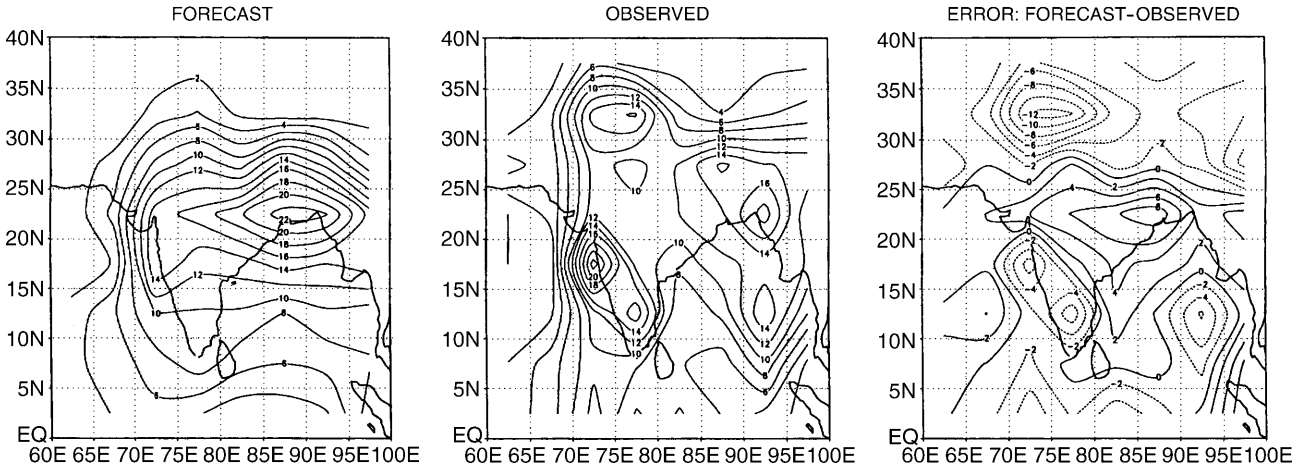

Fig. 7. Same as Fig. 1 for entire monsoon, 1997 (June–September)

east of Western Ghats of India and another over northeast India near lat. 25° N/long. 91° E (15 mm/day). Rainfall over the western end of monsoon trough is not reflected in the forecast pattern. Mean error indicates over-estimation of rainfall over a small domain centered at lat. 17° N/long. 80° E (6 mm/day). Otherwise, almost in all other parts the forecast is under-estimated, especially, over Western Ghats of India and the region north of lat. 30° N.

In August, observed rainfall continues to describe similar pattern with rainfall peaks over western Ghats of India centered at lat. 21° N/long. 74° E (22 mm/day) and two peaks over the region of monsoon trough at lat. 21° N/long. 92° E (20 mm/day) and at lat. 27° N/long. 84° E (18 mm/day). The forecast mean reproduces only one heavy rainfall domain over northeast India centered at lat. 27° N/long. 91° E (30 mm/day). Mean error shows over estimation of rainfall along a region covering north-east India to south wards upto Sri-lanka. Rainfall along west coast of India and north of lat. 30° N are under-predicted. It is very encouraging to note that in September when monsoon westerlies are weak (resulting in reduction of orographic rainfall) there exists a very good corresponds between forecast and observed rainfall, both reproducing identifiable rainfall distribution with one maxima centered near lat. 22° N/long. 91° E (15 mm/day).

In October also identifiable rainfall pattern is noticed. In this month heavy rainfall belt shifts over south Peninsula. Both forecast and observed patterns could capture the rainfall peak of the order of 12 mm/day centered near lat. 11° N/long. 77° E.

In November, maximum observed rainfall (15 mm/day) is located over south-west Bay of Bengal and adjoining land areas with center near lat. 12° N/long. 82° E. The forecast shows three peaks located near lat. 10° N/long. 80° E, lat. 12° N/long. 67° E (12 mm/day each) and lat. 18° N/long. 92° E (15 mm/day). In the forecast rainfall maxima over south Peninsula is found to shift to the west from the east coast.

Figure 7 shows rainfall pattern for the entire monsoon season (June–September) of 1997. The spatial pattern of observed rainfall is somewhat similar to the predicted rainfall, but with relatively higher over Western Ghats (called as box I) and over a pocket in north India (box III) and relatively lower over northeast parts of the country (box II). The model over-predicts (mean error around 5 mm) convective precipitation over the area of monsoon disturbance. Where as prediction is under-estimated (mean error around 5 mm) over the Western Ghats and also over the domain of heat low in north India. Under-estimation of orgraphy rainfall may be due to unresolved orography effect. Orographic lifting of monsoon westerlies cause heavy rainfall over the region.

Figure 8a displays the latitudinal variation of zonal averaged time mean rainfall for the south-west monsoon 1997. From equator to lat. 18° N, both forecast and observed rainfall are seen to coincide. Forecast shows a sharp peak around lat.

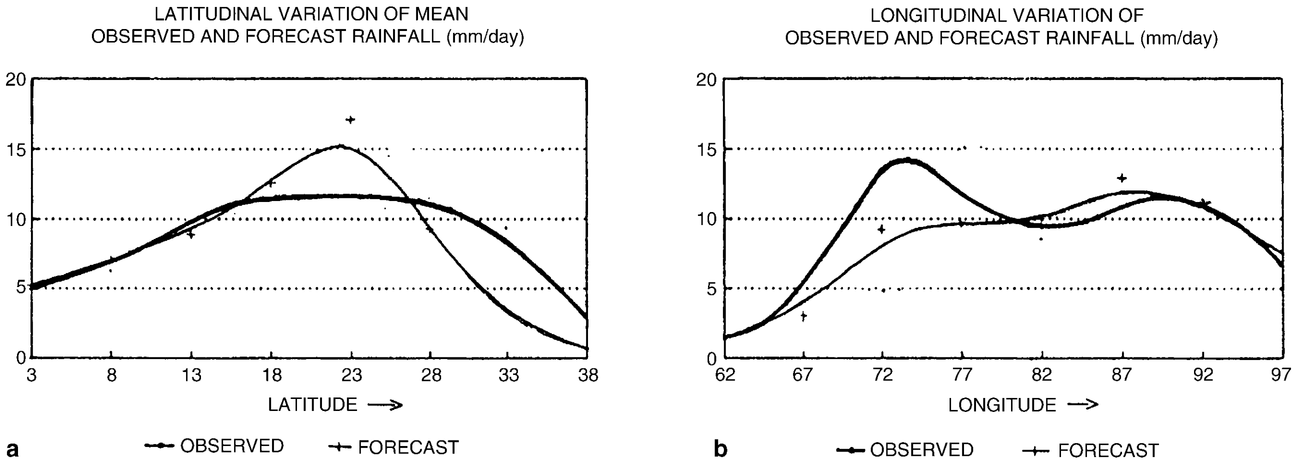

Fig. 8a. Latitudinal and **b** longitudinal variation of mean rainfall (mm/day) based on forecast and observation of south-west monsoon, 1997

22° N, along the domain of monsoon low, for the observed rainfall the peak is flat. Between lat. 18° N and 26° N mean forecast rainfall is higher by 2–4 mm/day where as north of 26° N this is lower by 5 mm/day. In the longitudinal variation (Fig. 8b) both forecast and observed mean rainfall show two peaks located at longitude 72° E, along Western Ghats and at 90° E in the domain of monsoon depression. The peak of observed rainfall along lat. 72° E is very sharp and higher by 5 mm/day compared to forecast.

3.2 Time series and categorical statistics

The time series for space mean predicted and observed rainfall for the entire domain and the spatial correlation coefficient (CC) between forecast and observed rain are shown in Fig. 9a, b. The data set for this series is based on area mean daily rainfall of June–September, 1997 for the Indian continent only. The series shows good correspondence between forecast and observed rainfall. The model is able to reproduce ups and downs of daily rainfall. The CC ranges from 0.4 to 0.8 and the mean CC is above 0.6.

In order to compare the behavior of daily forecast rainfall spells with reference to observed rainfall in case of orography (square box I) and monsoon low (square box II), the time series of predicted and observed areal average rainfall for a 5° × 5° lat./long. square box centered over west coast of India near lat. 17.5° N/long. 72.5° E (square box I) and over eastern part of country near lat. 22.5° N/long. 87.5° E (box II) are shown in Fig. 9c, d. Though model could reproduce ups and downs of daily rainfall spells, rainfall is always under predicted for the square box I and over-estimated for the square box II.

A comparison table showing the mean skill scores (bias and threat) at different rain threshold for the entire domain and period, for the 5 × 5 degree square lat./long. grid boxes centered over lat. 17.5 degree N and long. 72.5 degree E (box I), lat. 22.5 degree N and long. 87.5 degree E (box II), lat. 32.5 degree N and long. 77.5 degree E (box III), respectively is given below:

Rain threshold (mm)	Entire domain		Box I		Box II		Box III	
	Bias	Threat	Bias	Threat	Bias	Threat	Bias	Threat
01	1.18	0.72	1.06	0.94	1.00	1.00	0.55	0.53
10	0.87	0.32	1.00	0.53	1.50	0.57	0.19	0.13
20	0.80	0.20	0.84	0.50	2.57	0.32	0.10	0.12
30	0.70	0.18	0.40	0.21	4.25	0.16	0.16	0.11
40	0.60	0.15	0.65	0.00	5.5	0.16	0.16	0.11

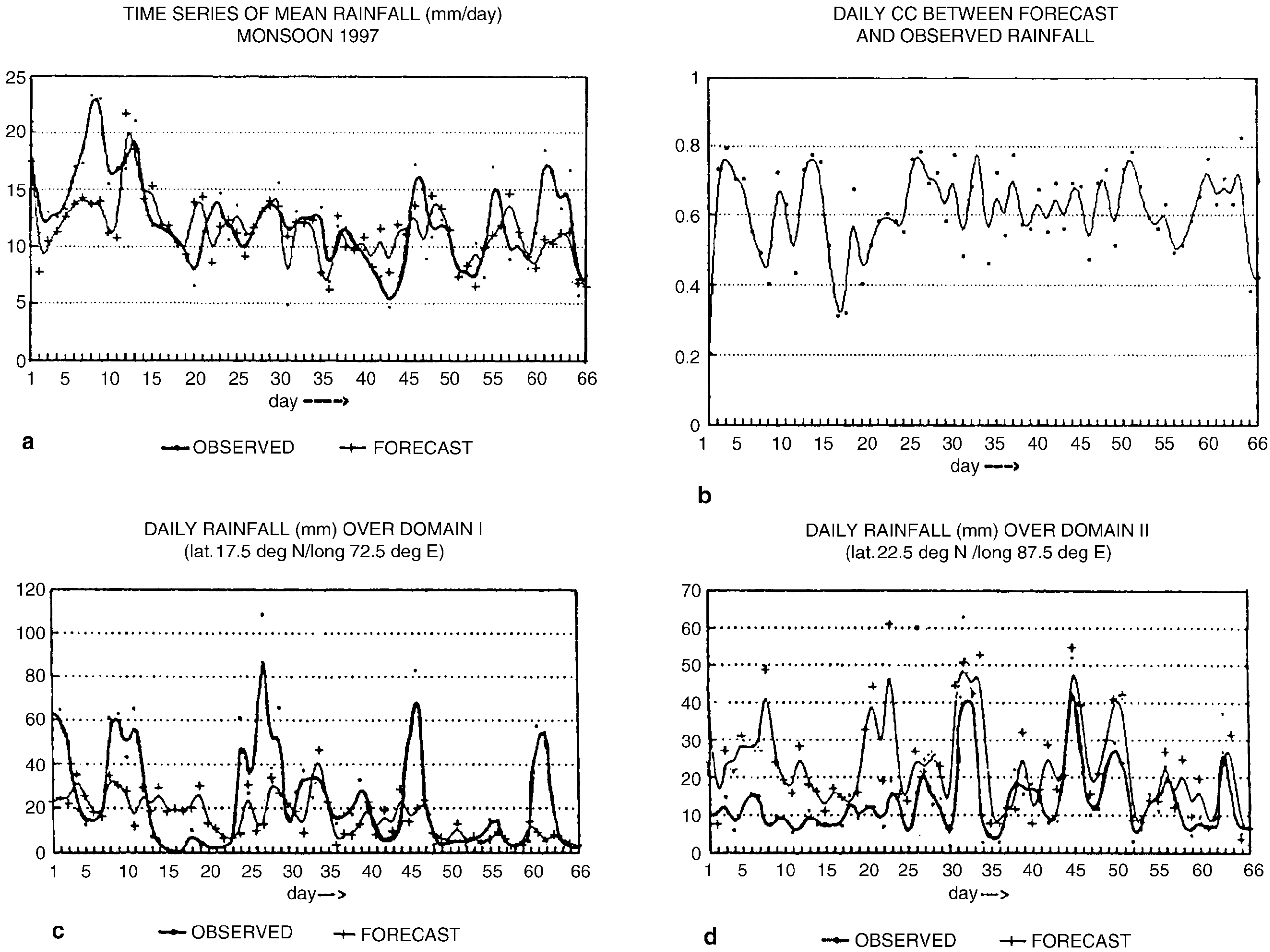

Fig. 9a. Time series of forecast and observed mean rainfall (mm/day) for south-west monsoon, 1997; **b** Time series of spatial correlation co-efficient between forecast and observed rainfall of Monsoon, 1997; **c** Same as in Fig. 9a for the 5° × 5° lat./long. square box centered over lat. 17.5° E/long. 72.5° N; **d** Same as in Fig. 9a for the 5° × 5° lat./long. square box centered over lat. 22.5° E/long. 87.5° N

It may be seen that for the box I rainfall is under-predicted for the rain threshold above 1 cm and threat score upto 2 cm rainfall is very good. For the box II, rainfall is over-estimated for rain threshold above 1 mm and threat score upto 2 cm rainfall is good. For the box III, rainfall is always under-forecast and threat score is very poor. However for the entire domain as a whole, bias and threat scores upto 2 cm rainfall are reasonably good.

These results are comparable with the results from operational NWP-models of other countries. With the exception of Ebert and McBride (1997), and Junker et al. (1992, 1989), most of the available studies are based on few case studies only and lacks proper representation of longer term verification data set. The present verification results have many points in common with the result of Ebert and McBride (1997). From the data set for the period from 12 June 1995 to 21 November 1996 based on LAPS (operational limited area model of Bureau of Meteorology, Australia) forecast over Australia region they found that in the seasonal map pattern rainfall is over-estimated over the wet region and under estimated over the mountain region. Mean monthly error and correlation coefficient between analyzed and forecast rainfall over Australia region are respectively 7.7 mm and 0.72, respectively as revealed in their study.

Junker et al. (1989) with 100 days data set of warm season during 1982 and 1983 found that for

NMC's regional model bias score for rain threshold 12.7 mm ranges from 0.6 to 1.6 and threat score from 0.2 to 0.4.

A comparison table showing average bias and threat scores for 1 mm and 10 mm rainfall for different NWP-models is given below:

Model	Rain threshold (mm)	Bias	Threat
LAM (IMD)	01	1.18	0.72
	10	0.87	0.32
LAPS (Ebert and McBride, 1997)	01	1.30	0.45
	10	1.10	0.30
NGM (Junker et al., 1992)	01	–	–
	10	0.70	0.32

These figures indicate that area averaged score for the LAM over Indian region during monsoon months are relatively better.

4. Evaluation of flow pattern forecasts

In this section mean flow patterns of forecast and analysis fields of following parameters of August, 1997 are compared and discussed:

4.1 Mean sea-level pressure

The climatology of mean sea-level pressure over India during the south-west monsoon season is dominated by a heat low located over Pakistan and adjoining areas. A trough of low pressure extends from this heat low to the head Bay of Bengal. The pressure increases towards south reaching a maximum value of about 1010 hPa. The pressure gradient along the west coast of India is taken as indicator of monsoon activity through enhanced moisture advection. Low pressure value of monsoon trough region indicates more activity due to genesis and movement of low-level circulations.

The minimum value of mean MSL pressure (1000 hPa) obtained in 24 hours forecast (Fig. 10) lies over north-west India near lat. 25° N/long. 75° E and extends east west wards along the region of monsoon trough between lat. 20° N and 25° N. In the mean analysis, two low pressure areas near lat. 30° N/long. 65° E and lat. 27° N/ long. 73° E (minimum value 998 hPa each), over the region of monsoon trough are located. The trough region in the analysis is comparatively narrow and runs from east coast of India at lat. 22° N to north-west wards across these low pressure areas. Forecast MSL-pressure over the domain of monsoon trough is higher by an order ranging 2 hPa at the east end to 6 hPa at the west end of the trough. Forecast MSL-pressure is slightly lower over central and southern parts of the country between lat. 10° N to 22° N.

4.2 Lower tropospheric circulation

The circulation pattern during south-west monsoon over India at 850 hPa is characterized by east-west oriented wind trough with normal position along lat. 22° N in August. The eastern part of the trough is located in it's normal position

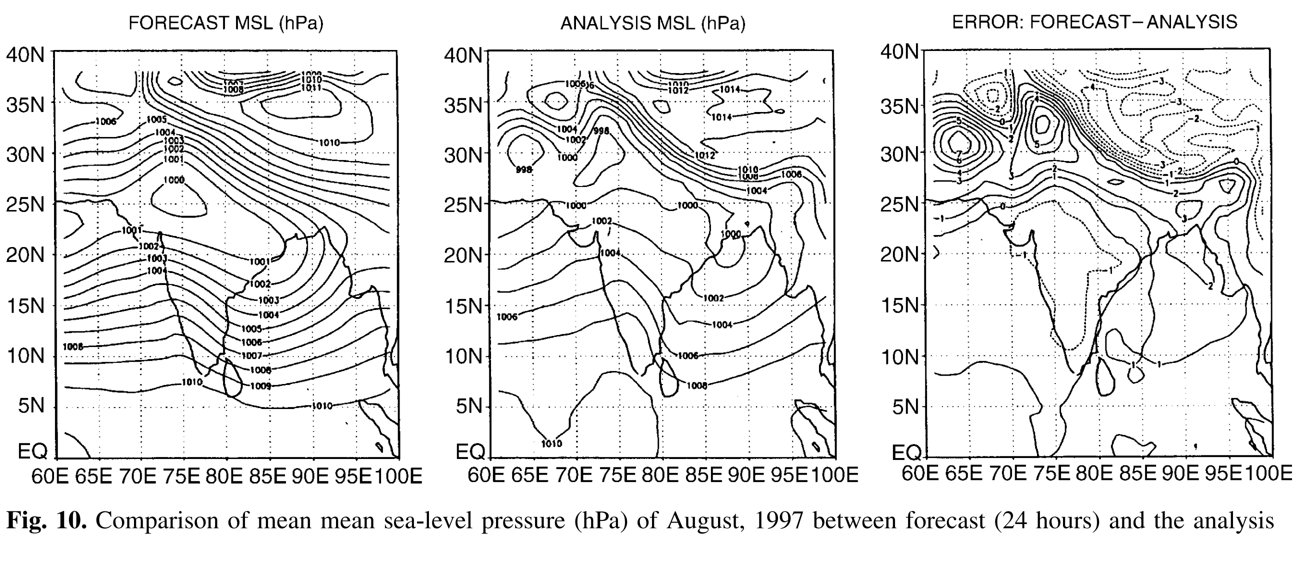

Fig. 10. Comparison of mean mean sea-level pressure (hPa) of August, 1997 between forecast (24 hours) and the analysis

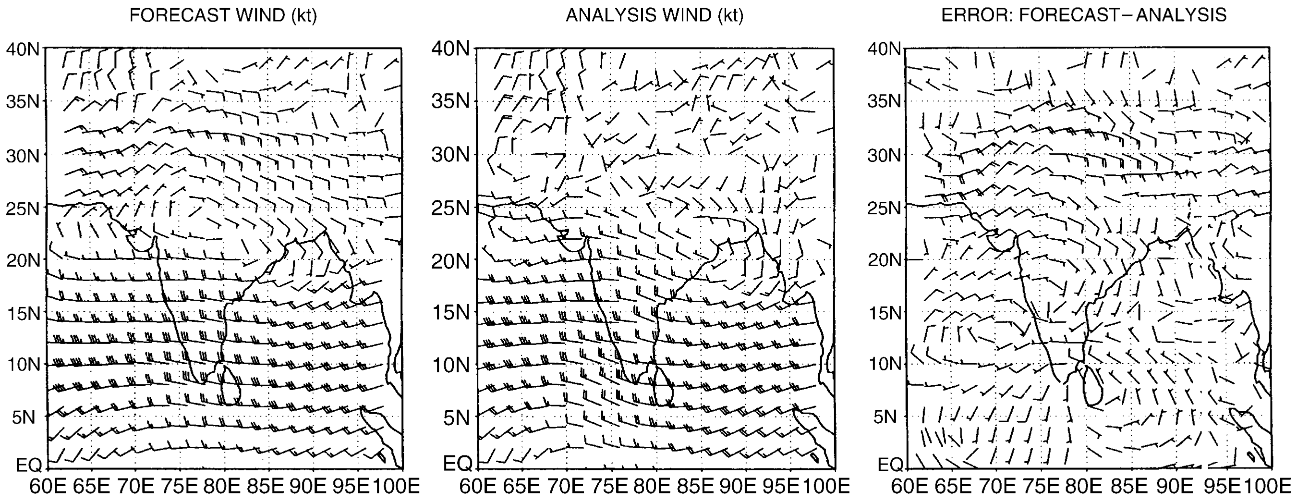

Fig. 11. Same as Fig. 10 for the mean wind field (kt) at 850 hPa

in the mean analysis field (Fig. 11) with a circulation near lat. 23° N/long. 85° E. The trough extends northwest wards and meets with another circulation lay near lat. 27° N/long. 65° E, where as forecast field shows a circulation near lat. 22° N/long. 77° E with a trough between lat. 21° N and 22° N. Monsoon westerlies from the Arabian Sea with averages speed 20–25 knots is noticed in the analysis field. Forecast westerlies to the south of trough line along Western Ghats are weaker by 5 knots and south of 10° N westerlies are stronger by the same strength. Similar features are noticed at 700 and 500 hPa also. The forecast low-level westerlies along Western Ghats are also noticed weaker compared to analysis during the episode of monsoon depression (fig. not shown). South ward shifting of trough with height is seen in the forecast field as in the analysis.

4.3 Upper tropospheric circulation

The south-west monsoon circulation over India at 200 hPa is dominated by an anticyclone over Tibet region separating the westerly jet to the north and easterly to the south. Both forecast and analysis (Fig. 12) broadly depicts same pattern with ridge line located along lat. 24° N. Forecast easterlies south of the ridge are stronger by 10 knots and to the north westerlies are stronger by same order.

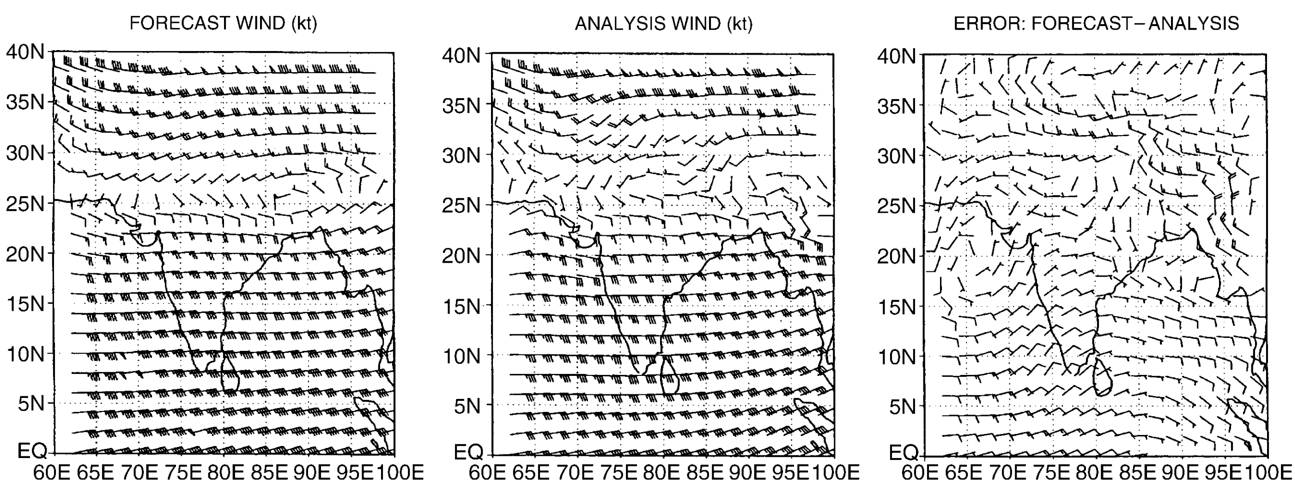

Fig. 12. Same as Fig. 10 for the mean wind field at 200 hPa

5. Vertical profile

In Sect. 3, it was discussed that the orographic rainfall along Western Ghats of India during south west monsoon season are under-predicted. In this section we compare vertical profiles of relative humidity, relative vorticity, divergence and vertical motion between forecast and analysis for the 2° × 2° lat./long. square box over Western Ghats centered at lat. 17.5° N/long. 72.5° E based on daily forecast and analysis field of August, 1997. Again during north-east monsoon, the heavy rainfall belt is mainly confined over South Peninsula. In order to compare the vertical structure between forecast and analysis field of convective rainfall in association with north-east monsoon, temporal area mean vertical profiles are constructed over a 2° × 2° lat./long. box centered at lat. 12.5° N/long. 77.5° E. based on daily forecast and analysis field of November 1997. The comparison results are discussed below:

5.1 Orography rainfall along Western Ghats

Figure 13a–d illustrates the comparison of mean vertical profiles between forecast and observed for (a) relative humidity, (b) relative vorticity, (c) divergence and (d) vertical motion (omega) for orography rainfall for the small box over Western Ghats of India. The profile of relative humidity shows that forecast humidity is lower at all levels, ranging from 50% at lower tropospheric levels to 10% at the mid-tropospheric levels. The profiles both for forecast and analysis show cyclonic vorticity upto 400 hPa and then anticyclonic vorticity follows. Below 850 hPa cyclonic vorticity of analysis field is slightly stronger, but between 850 and 400 forecast vorticity is stronger. In case of divergence, from lower most levels to 700 hPa forecast field shows divergence where as analysis shows convergence, at 700 hPa both becomes zero, extends upto 600 hPa and then divergence starts. Above 700 hPa both profiles are coinciding.

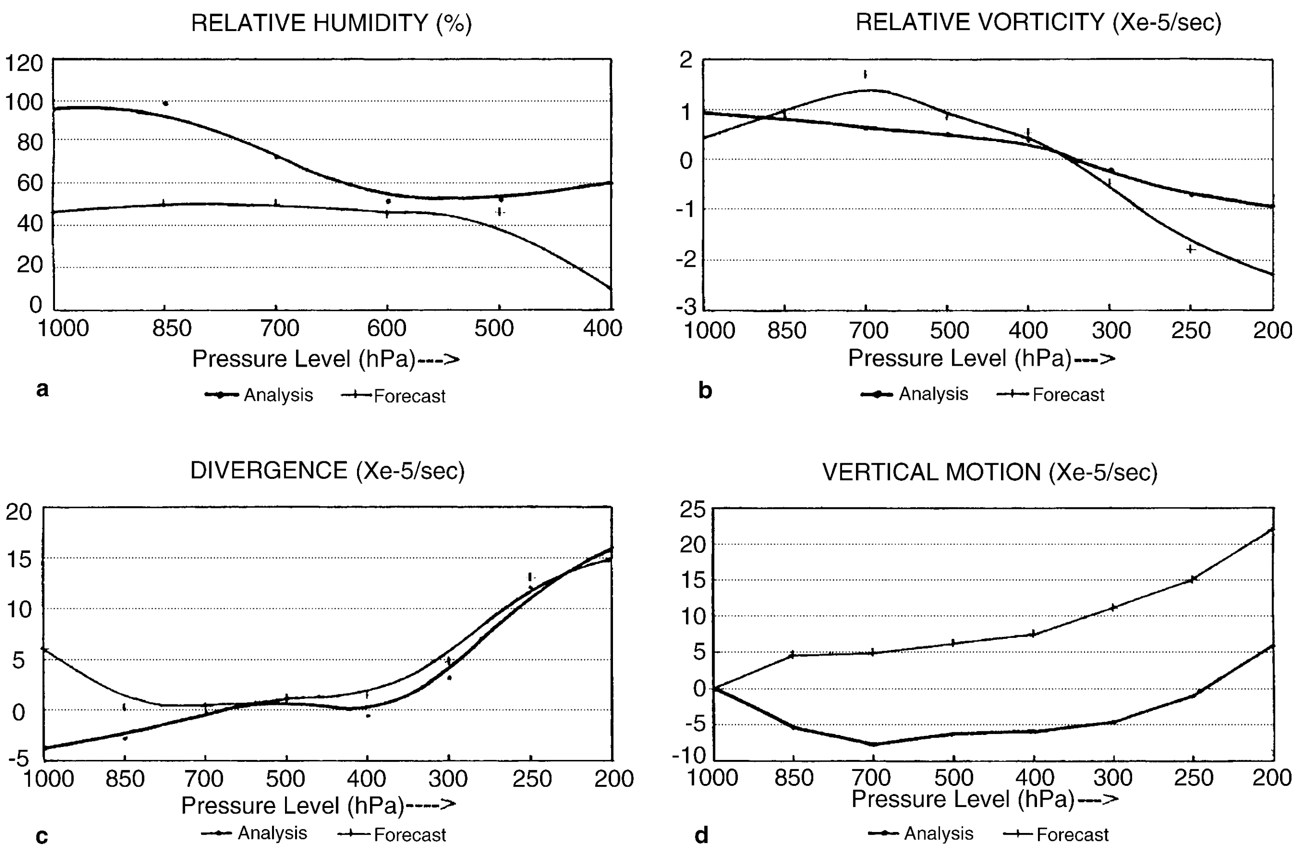

Fig. 13. Comparison of mean vertical profile of **a** relative humidity (%), **b** relative vorticity ($\times 10^{-5}$/sec), **c** divergence ($\times 10^{-5}$/sec), and **d** vertical motion ($\times 10^{-5}$/sec per hPa), of August, 1997 between forecast and the analysis over a 2° × 2° lat./long. square box centered at lat. 17.5° N/long. 72.5° E in association with orography rainfall

The forecast profile of vertical motion largely differs with the analysis. The analysis field shows ascending motion upto 250 hPa, where as forecast shows larger descending motion at all levels.

5.2 North-east monsoon rainfall over south Peninsula

Figure 14a–d present vertical profiles in case of north-east monsoon rainfall for the small box over south Peninsula. The relative humidity profile shows that forecast humidity is large at all levels, particularly in the lower tropospheric levels where forecast humidity is higher by 15% and is consistent with the higher rainfall amount produced by the forecast. Relative humidity becomes zero above 250 hPa. The relative vorticity profiles both for analysis and forecast are very similar upto 250 hPa. The profiles show cyclonic vorticity upto 700 hPa and then anticyclonic vorticity follows. Above 250 hPa for the forecast anticyclonic vorticity gradually becomes zero where as for the analysis profile continues negative vorticity above 250 hPa and differs from forecast. An interesting aspect of convective rainfall is that it carries a vertical structure of lower-levels convergence and upper-level divergence and order of divergence is higher than vorticity field. In this case, analysis field is showing maximum convergence at 500 hPa, but in the forecast maximum convergence extends upto 700 hPa and then gradually decreases to zero at 300 hPa. Forecast seems to under-estimate large upper tropospheric diver-

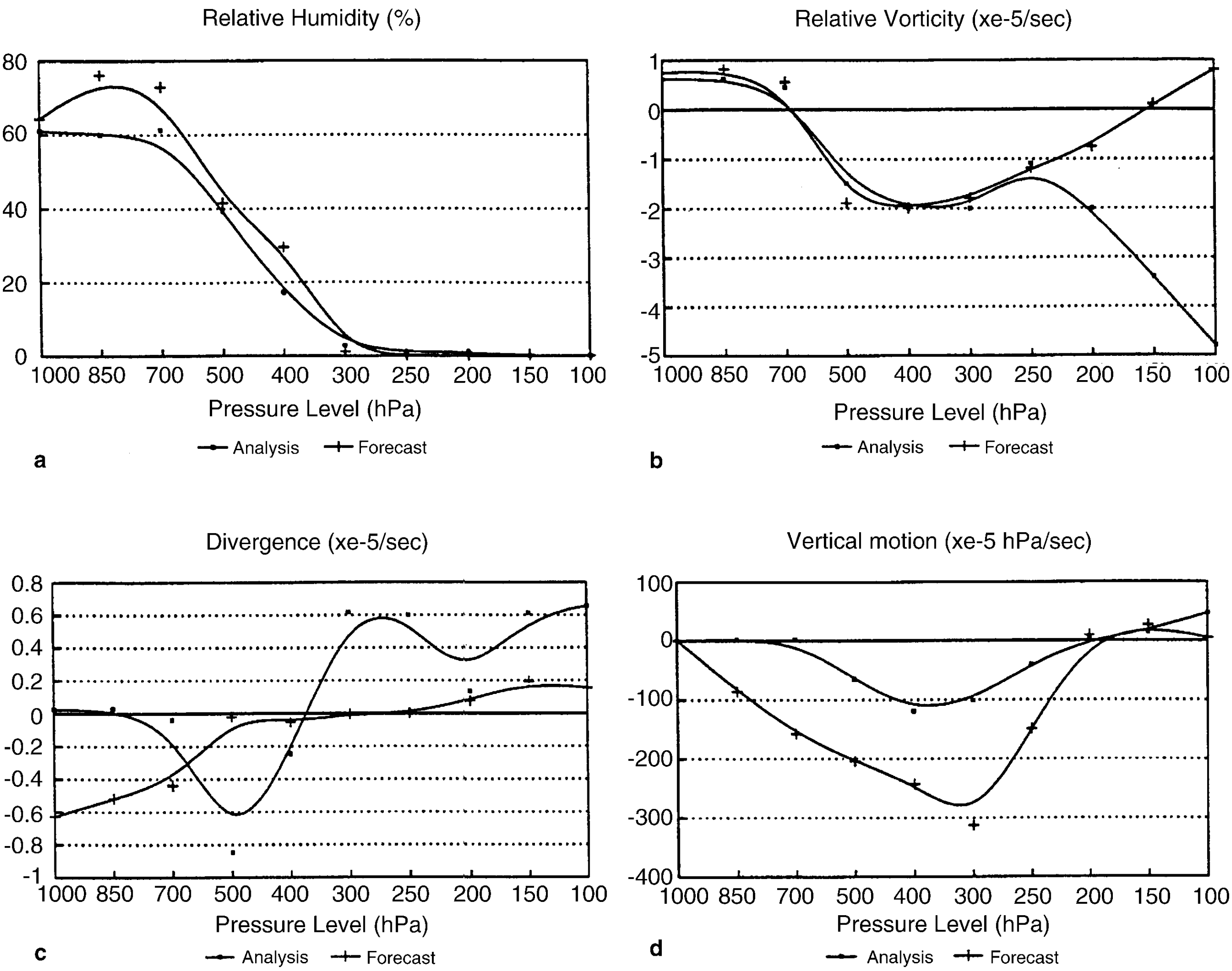

Fig. 14. Comparison of mean vertical profile of **a** relative humidity (%), **b** relative vorticity ($\times 10^{-5}$/sec), **c** divergence ($\times 10^{-5}$/sec), and **d** vertical motion ($\times 10^{-5}$/sec per hPa), of November, 1997 between forecast and the analysis over a 2° × 2° lat./long. square box centered at lat. 12.5° N/long. 77.5° E in association north-east monsoon rainfall

gence as observed in the analysis. Strong vertical upward motion over the convective rainfall domain is clearly apparent in both the omega profiles of analysis and forecast. Maximum ascending motion is noticed between 400 hPa and 300 hPa. However, the forecast seems to have some bias toward large ascending motion.

6. Summary and conclusions

This study demonstrates that performance of the numerical model in predicting precipitation varies with month, geographic location and by synoptic regime. The model, in general, is able to reproduce the spatial pattern of monthly and seasonal rainfall but biases of the model fluctuates significantly. For the two heavy rainfall belts; one orography rainfall over Western Ghats of India and another in north-west part of India over the domain of heat low, rainfall is under-predicted during June to August where as rainfall over north-east part of the country is over-predicted. The under-estimation of orography rainfall could be due to the fact that terrain (topography) at the model resolution is not high enough. But an encouraging result is the very high degree of agreement between forecast and observed rainfall distribution in the month of September and October when lower tropospheric westerlies along Western Ghats are weak. In October and November when low-pressure belt shift to the southern latitude of India, the model is able to capture heavy rainfall zone confined over south Peninsula. Time series and categorical statistics show that there is a very good correspondence between observed and predicted rainfall. The model is able to capture ups and downs of daily area mean rainfall spells. The over all performance of the model appears to be skillful and comparable with the results of other operational models like LAPS of Australia and NMC's regional model.

The other important features of south west monsoon such as: mean sea-level pressure distribution with a heat low over north-west India, monsoon trough separating westerlies to the south and easterlies to the north and its equatorward tilt with height, upper tropospheric easterly and westerly jets are reproduced in the forecast and are comparable with those of analysis fields. But some of the significant deficiencies noticed in the forecast are: higher mean sea-level pressure, particularly over the domain of heat low and relatively weaker lower tropospheric westerlies.

Comparison of vertical profile reveals that in case of the orography rainfall over Western Ghats, though model is able to reproduce vertical structure of relative vorticity and divergence, but largely differs in case of vertical motion and relative humidity. Vertical motion shows large descending motion in all levels and relative humidity shows dry atmosphere. For the north-east monsoon over south Peninsula profiles are reasonably matching with analysis except the fact that model produces higher ascending motion.

The results of this study are expected to provide important input for operational forecaster and useful feed back for future modification of NWP-system improving initialization and parametrization schemes intended for operational use.

Acknowledgements

The authors are grateful to Dr. R. R. Kelkar, Director General of Meteorology, India Meteorological Department, New Delhi for providing all facilities to carry-out this research work and giving permission for publication of the paper in this journal. Authors are also grateful to Shri A. M. Sud, Deputy Director General of Meteorology for his encouragement and keen interest in this study.

References

Arkin PA, Rao AVRK, Kelkar RR (1989) Large-scale precipitation and out-going long-wave radiation from INSAT-1B during 1986 south-west monsoon season. J Clim 2: 619–628

Basu BK, Ramesh KJ, Harathi PA (1999) Intercomparison of the characteristic features of south-west monsoon over India as reproduced in the mean monthly analysis and forecast of some operational NWP Centers during 1995. Met Atmos Phy 69: 157–178

Ebert EE, McBride JL (1997) BMRC Techniques Development Report No. 2, Bureau of Meteorology and Research Center, Melbourne, Australia

Jensenius JS (1990) A statistical comparison of the forecast produced by the NGM and LFM for 1987/88 cool season. Weather and Forecasting 5: 116–127

Junker NW, Hoke JE, Grumm RH (1989) Performance of NMC's regional model. Weather and Forecasting 4: 368–390

Junker NW, Hoke JE (1990) An examination of Nested Grid Model precipitation forecast in the presence of moderate to strong low-level southerly inflow. Weather and Forecasting 5: 333–344

Junker NW, Hoke JE, Sullivan BE, Brill KF, Hughes FJ (1992) Seasonal and geographical variation in quantitative precipitation prediction by NMC's Nested Grid model and medium range forecast model. Weather and Forecasting 7: 410–429

Krishnamurti TN, Kumar A, Yap KS, Dastoor AP, Davidson N, Sheng J (1990) A documentation of the FSU Limited Area Model, FSU report no. 89/4, 302 p

Stanski HR, Wilson LJ, Burrows WR (1989) Survey of common verification methods in meteorology, WMO/TD no. 358, WMO, Geneva

Authors' address: S. K. Roy Bhowmik and K. Prasad, NHAC (NWP), Mausam Bhavan, Lodi Road, New Delhi-110003, India (E-mail: kprasad@imd.ernet.in)