Effect of Grid Resolution on the Simulation of Orographically Induced Precipitation

KIRANKUMAR ALAPATI, RANGA RAO V. MADALA* AND SETHU RAMAN

Department of Marine, Earth and Atmospheric Sciences
North Carolina State University,
Raleigh, NC 27695-8208, U.S.A.

* *Atmospheric Physics Branch*
Naval Research Laboratory
Washington, D.C., U.S.A.

1. INTRODUCTION

During the Southwest Monsoon season western coast of the Peninsular India is one of the areas where frequent large rainfall rates are observed. This region is of particular interest because (i) lower level monsoon Westerlies approach the Western Ghat mountains almost at right angles after travelling thousands of kilometres over Indian Ocean and Arabian Sea, and (ii) prevailing convective instability can trigger deep convection giving rise to rainfall. These Ghat mountains which run parallel to the west coast are about 50 km inland. Raingauge data analysis by Ramakrishnan and Gopinatha Rao (1958) and Ramachandran (1972) revealed that the intense rainfall is concentrated upstream (coastwards) of the Ghat mountains though the seaward extension of this rainfall was not clear until the combined analysis of satellite and raingauge data by Krishnamurti *et al.* (1983) was available. Their analysis shows that the preferred location of the rainfall maximum is not over mountain peaks but offshore. Their analyzed rainfall distribution shows considerable spatial and temporal variation during the 1979 monsoon season with a maximum rate of ~ 200 mm/day over the Arabian sea and near the west coast. Satellite-based cloud imagery was used in estimating the rainfall over the oceans utilizing a simple regression analysis. Numerical simulation studies can provide more insight into the processes involved.

Analytical study by Smith and Lin (1983) using a steady state model revealed that the dynamic forcing by the Ghat mountains alone is insufficient to produce the observed rates of rainfall but the heating computed from the observed rainfall indicated an environment favourable for cumulonimbus development. Utilizing the aircraft observations over the Arabian sea and using an analytical nonlinear mountain-flow interaction model, Grossman and Durran (1984) concluded that Ghat mountains are capable of producing off-shore convection. The lifting predicted by a two-dimensional model was applied to mean dropwindsonde soundings for the days with and without offshore convection and it was found that spells in the rainfall can be attributed to the cooler surface layer. Grossman and Durran (1984) speculated that the dry layer above the boundary layer might have originated from the Arabian desert. Using a cloud model Ogura and Yoshizaki (1988) showed that the fluxes of sensible heat and moisture from the ocean and a sheared environment are two important factors that influence the intensity and location of the rainfall near the Ghat mountain region.

The important features can be summarized as:

(i) Ghat mountains can provide orographic lifting to the air parcels

(ii) Prevailing convective instability can lead to deep convection

(iii) The Arabian sea might feed moisture to the atmosphere

(iv) Vertical wind shear can alter the location of the rainfall maximum

These processes should be realistically represented in order to simulate the observed spatial and temporal structure of the orographic-convective rainfall. To include the possible role of large scale flow field besides these processes a fairly large region should be covered. In order to meet all these requirements one may need a three dimensional numerical model with good initial conditions. The present study makes an attempt to numerically simulate the orographic-convective rainfall near the Ghat mountains region using a three dimensional mesoscale nested grid model. In accomplishing the objective of the present work a period with large rainfall rate was selected and numerical simulations were done for 48 hours.

2. DESCRIPTION OF THE NESTED GRID MODEL

The model used in the present study is the one developed by Naval Research Laboratory and North Carolina State University. This is a primitive equation model in terrain following coordinates having a one-way interacting nested grid network. The continuous governing equations are written in flux form. The time integration scheme utilized in the present model is the split explicit method which allows larger time step by effectively separating various terms in prognostic equations into parts governing the slow moving Rossby modes as opposed to fast moving gravity modes. For the first and second fast moving gravity modes smaller time step is used and for the third to fifth slow-moving mixed modes a large time step is used. The implementation of these varying time steps is the basis for the split-explicit method. For horizontal differencing a staggered grid network (Arakawa's C- grid) is used. The Fine and Coarse Mesh domains are user specified in which Fine Mesh (FM) grid overlaps one-third of the Coarse Mesh (CM) grid. The FM grid is nested into the CM grid such that every third FM grid is colocated with the CM grid. The nested grid is positioned such that its boundary rows and columns overlap the CM interior rows and columns. This nesting configuration enables the FM domain boundary values to be specified by the CM interior grid points. Perkey and Kreitzberg (1976) type lateral boundary conditions are employed in the present version of the model. Various physical processes such as flux transfer, stratified precipitation, dry and moist convection which are essential for short range weather prediction are parameterized in this model assuming short and long wave radiations to be less important. Bulk aerodynamic formulae are used to determine the surface transfer of momentum, sensible heat and latent heat. Cumulus convection parameterization suggested by Kuo (1974) and modified by Anthes (1977) is used in the model. If super-saturation exists at any level, large-scale precipitation is computed as the excess moisture which is allowed to condense and fall out to the next lower layer and evaporate or continue to fall depending upon the state of saturation at that level. Also in the model a dry convective adjustment is restored at every hour of integration. This instability is explicitly removed via an equal energy adjustment. A second order diffusion is used in order to account for the energy associated with unresolved subgrid scale processes.

First GARP Global Experiment (FGGE) level III A data set is utilized to specify the initial conditions. This analyzed data of 2.5° resolution at 12 vertical levels was used to interpolate to model grid points at 10 levels. Bicubic polynomial interpolation is used for horizontal fields and appropriate profiles were used for vertical interpolation from p-surfaces to σ-surfaces. Horizontal grid resolutions in the CM and FM models are 1.5° and 0.5° respectively and vertical grid resolution is 0.1 sigma. CM domain covers from 30° E to 120° E and 28° S to 50° N and FM domain from 54° E to 102° E and 5.5° S to 30.5° N. The time steps for slow moving modes in CM and FM are 300 s and 100 s and appropriate small time steps satisfying CFL condition were used for fast moving modes. Model integrations were carried out for 48 hours starting from June 24, 1979 00Z. Model grid topography for FM and CM domains are obtained from Navy 10 minute global topography data. The difference between the Ghat mountain peak in FM and CM domains is about 285 m. In the CM Ghat mountain peak is one grid distance away from west coast (~ 150 km) where as in FM this peak is away only 2 grid points from West Coast (~ 100 km). Since the present study uses a primitive equation model initial conditions must be smooth enough to avoid the spurious large amplitude gravity modes which arise during the time integration. These modes arise due to the imbalance in the initial conditions and can be removed efficiently via technique called normal mode initialization. Though we used the analyzed FGGE data the differences between the model and real atmosphere lead to the amplification of the fast moving small amplitude gravity modes. In order to have a smooth simulation nonlinear normal mode initialization technique similar to that suggested by Bourke and McGregor (1983) was employed.

3. RESULTS AND DISCUSSION

Simulations for the period (24 to 26 June 1979; 00 Z)

Figure 1 shows the domains covered by CM model and FM model with FM domain located over the Indian subcontinent. FGGE data sets are used to prescribe the initial conditions. A numerical experiment was performed using the data starting June 24, 1979; 00 Z and numerical integrations are carried out for 48 hours. There are 61 × 53 × 10 and 97 × 73 × 10 grid points in the CM and FM domains with 1.5° and 0.5° horizontal resolution. Maximum observed rainfall over the western ghat region during the period of simulation is ~ 169 mm/day and has considerable spatial variation. Monsoon depressions are very common over the Bay of Bengal and most of them travel in a north to northwest direction. During the period of simulation a monsoon depression was present and is simulated by CM and FM models. Coastal line in both CM and FM domains were determined based on the topography data and thick solid lines represent the coastal lines.

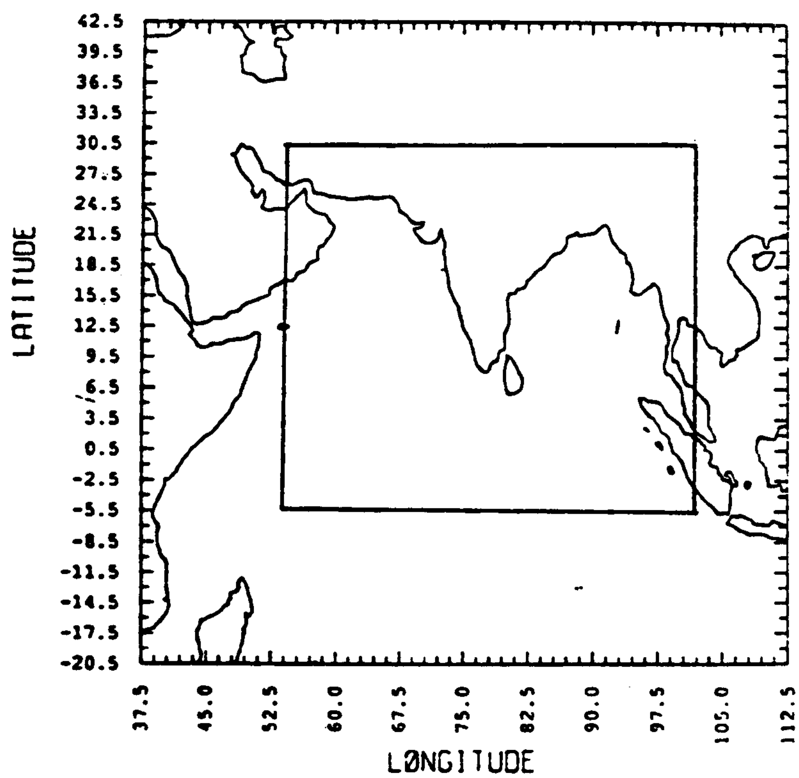

Fig. 1. Numerical model domain. Inner box is the area covered by the Fine Mesh (56 km × 56 km) and outer box is the area covered by the Coarse Mesh (168 km × 168 km)

Figures 2 and 3 show the observed wind field at 850 mb for 24 and 25 June 1979 at 12 GMT respectively. Corresponding FM model simulations at level $\sigma = 0.8$ are shown in Figs. 4 and 5 respectively. A monsoon depression which existed off the east coast was better simulated in FM model than in CM model (not shown). At 24 June 1979, 12 Z observed monsoon depression (Fig. 2) was

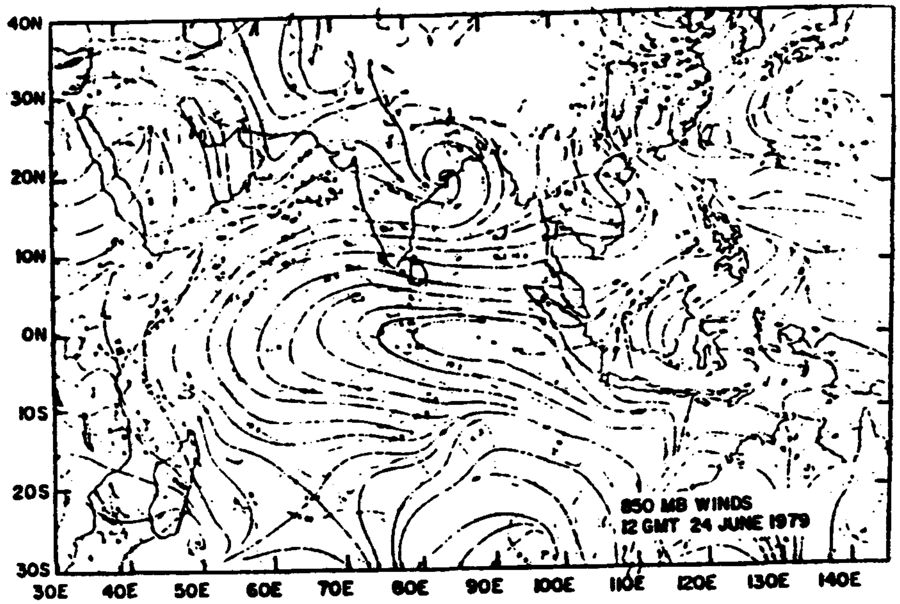

Fig. 2. Observed wind field at 850 mb level at 12 GMT of June 24, 1979. Monsoon depression is located over the east coast of India

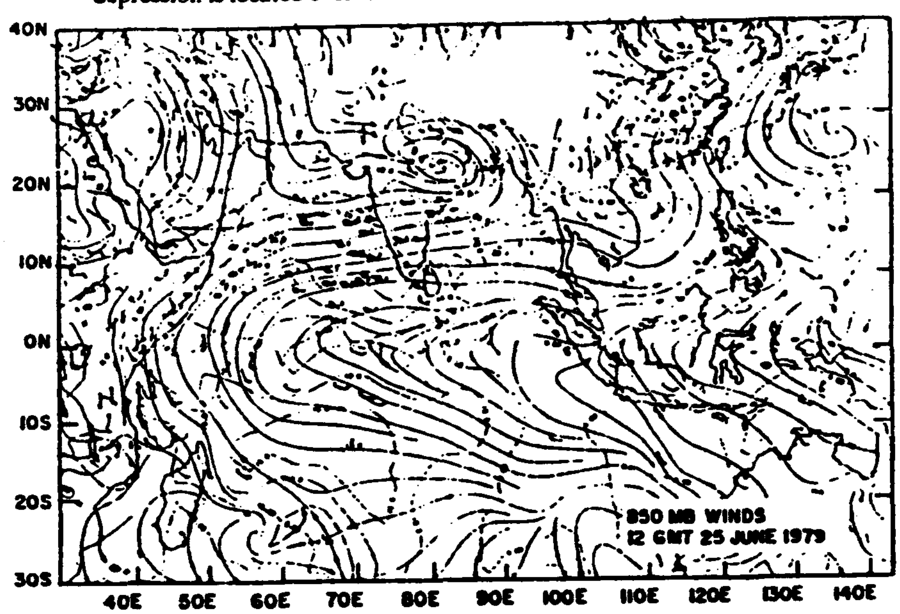

Fig. 3. Observed wind field at 850 mb level at 12 GMT of June 25, 1979. Monsoon depression has moved northwest and is located over northeast of India

located over the east coast of India and at 12 Z of next day (25 June 1979) this has moved further inland and was located over the northeast of India. In the CM domain this depression has moved north (not shown) and was located over Head Bay at 12 Z of 25 June 1979 whereas in FM domain it has moved northwest and was located over eastern part of India (Fig. 5) which is close to the observed location. This shows the effect of model grid resolution on the simulation. Though the circulation patterns are more pronounced in fine

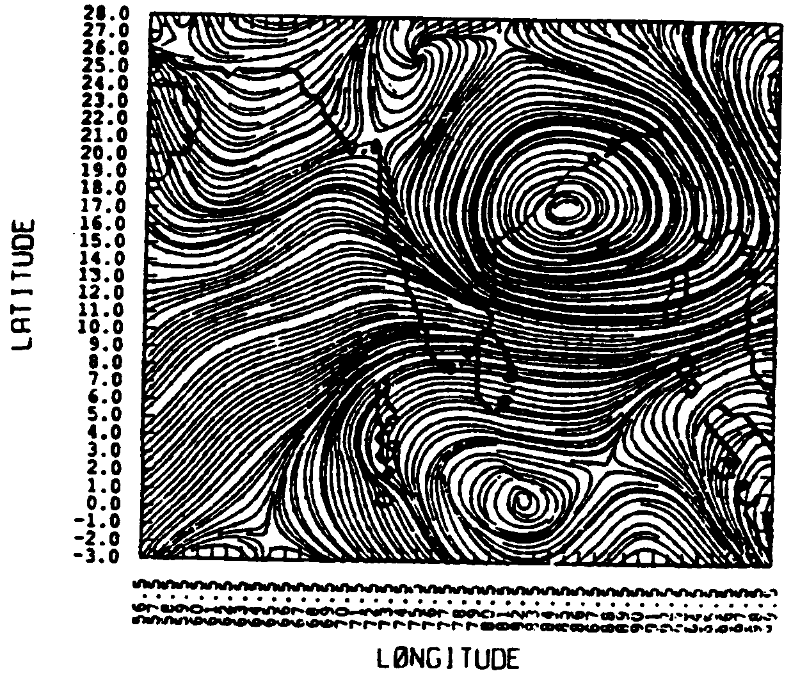

Fig. 4. Fine Mesh simulation of stream lines at 12 GMT of June 24, 1979. Monsoon depression is near to east coast of India

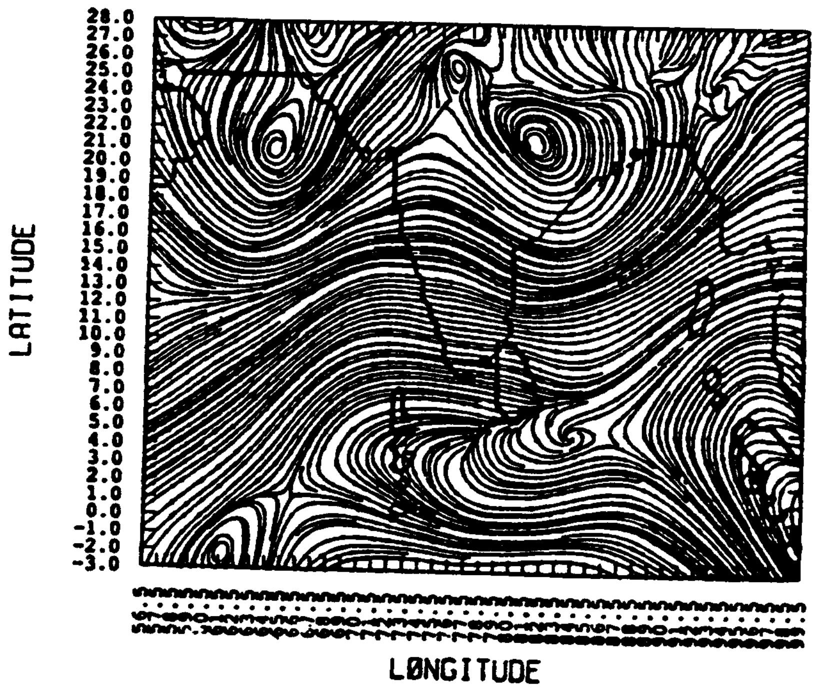

Fig. 5. Fine Mesh simulation of stream lines at 12 GMT of June 25, 1979. Monsoon depression is over the northeast of India

resolution model simulations they are closer to the observed fields than those in CM model simulations.

Figures 6, 7 and 8, 9 show the predicted rainfall (mm/day) by CM and FM models for 25 and 26 June 1979 ending 00 GMT. During the first day of simulation there is no offshore (over Arabian sea) precipitation in CM model (Fig. 6) and near the Ghat mountains rainfall is concentrated downstream and over mountain peaks. Rainfall over western Arabian sea (Arabian coast) is due to a wind surge which has travelled across the Arabian sea during this period. Young *et al.* (1980) showed that during the period 23 to 26 June 1979 wind surge moved with an average speed of 3-4° longitude per day. The predicted rainfall over this region can be attributed to this wind surge. Figures 10 and 11 show the isotachs predicted by CM and FM models at level $\sigma = 1.0$ (the lowest level in the models) corresponding to 25 June 1979, 00 Z respectively. In the CM domain the 15 m isotach was confined to southwest part of Arabian sea (Fig. 11) at the end of the 24 hour simulation whereas in FM domain it is located over central Arabian sea.

Figure 7 shows the rainfall prediction by FM model during the first day of simulation (mm/day). Rainfall patterns are somewhat similar in CM and FM domains (Figs. 6 and 7) but in the FM model offshore extension of rainfall can be seen near Ghat mountain region. The effect of the increase in the grid resolution can be seen from these figures. Observed rainfall maximum near Ghat mountain region is about 169 mm/day whereas the predicted rainfall by FM model was 30 mm/day but the spatial distribution of rainfall predicted by FM model is closer to the observation than by the CM model. The rainfall over western part of Arabian sea is more pronounced in the FM domain.

Observed rainfall due to monsoon depression which is located over the northeast region of India was about 100 mm on this day and prediction by FM model (Fig. 7) was about 50 mm with a spatial distribution very similar to the observed one. Rainfall prediction by CM model due to this depression is 55 mm and the spatial distribution is less comparable to the observation which reflects the effect of grid resolution. The dense rainfall patterns over the eastern parts of the FM and CM domains are due to the high mountains over these regions. The orographic orientation of the rainfall predictions by both models over these high mountains may be more numerical than physical. This may be due to the "horizontal" diffusion on sigma surfaces, particularly over significant inclined surfaces, where mixing of warm air at lower altitudes with cold air at higher altitudes may lead to the destabilization making precipitation more likely over this region.

Figures 8 and 9 show the rainfall prediction (mm/day) by CM and FM models for the second day ending 26 June 1979, 00 Z and the observed rainfall maximum over Ghat mountain region is about 155 mm. During the second day predicted rainfall by CM model extended off the west coast of India with a maximum over mountain peaks. The maximum rainfall over the Ghat mountain region predicted by CM model is about 37 mm/day (Fig. 8) and is located over the mountain peak with offshore rate of 20 mm/day. Rainfall due to the

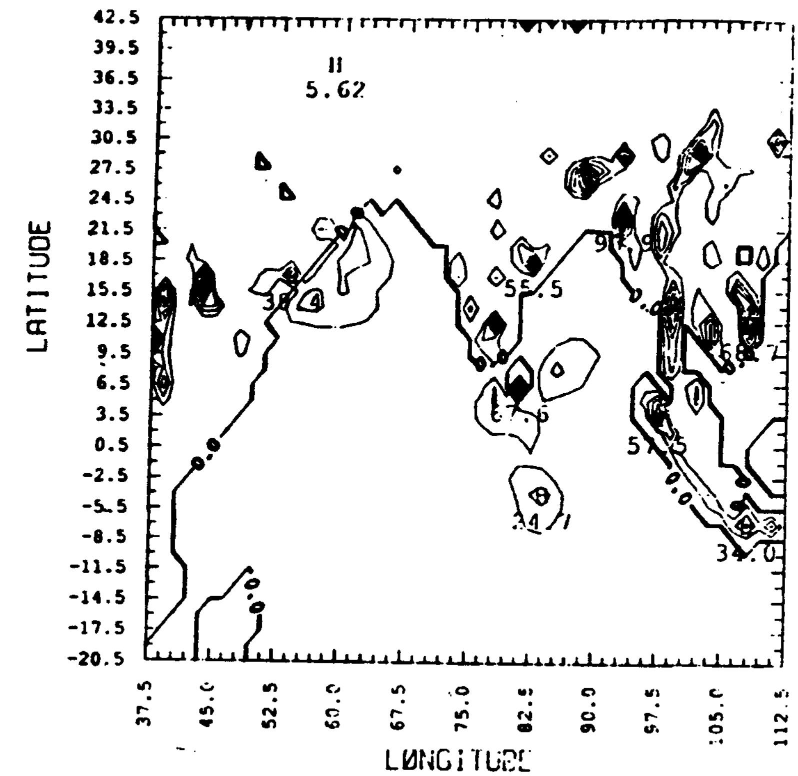

Fig. 6. Total rainfall (mm/day) predicted by the CM model during the first 24 hours of simulation

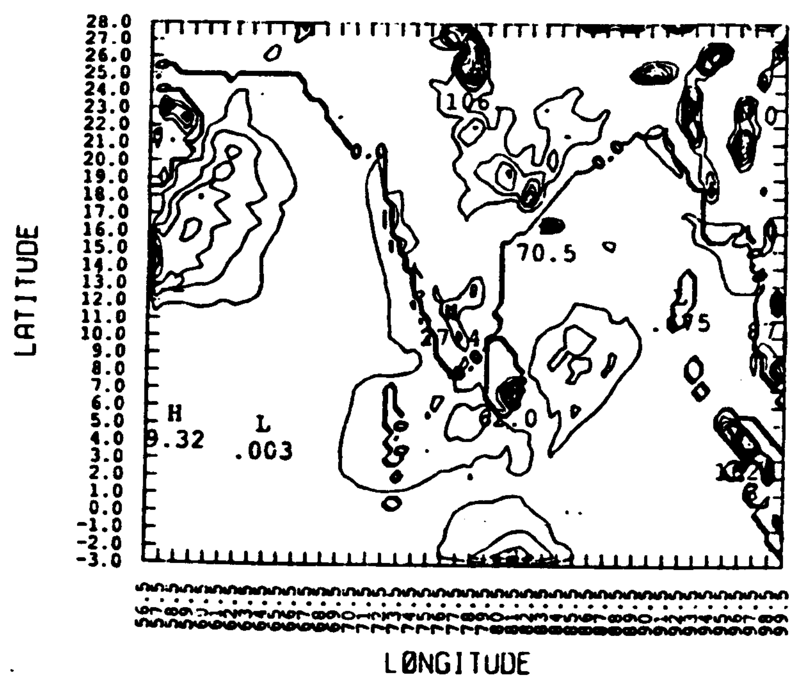

Fig. 7. Total rainfall (mm/day) predicted by the FM model during the first 24 hours of simulation

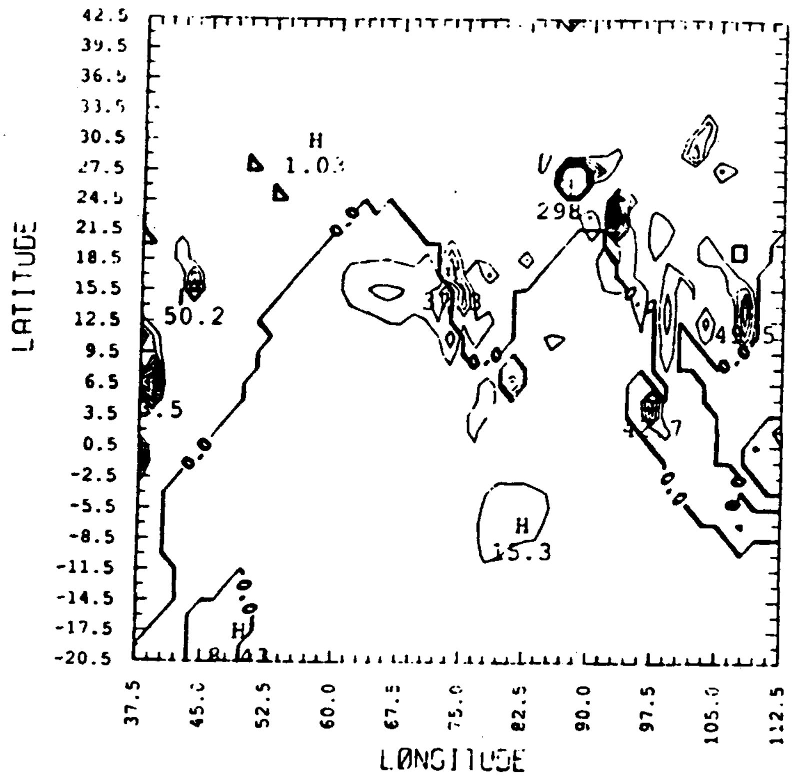

Fig. 8. Total rainfall (mm/day) predicted by the CM model during the second 24 hours of simulation

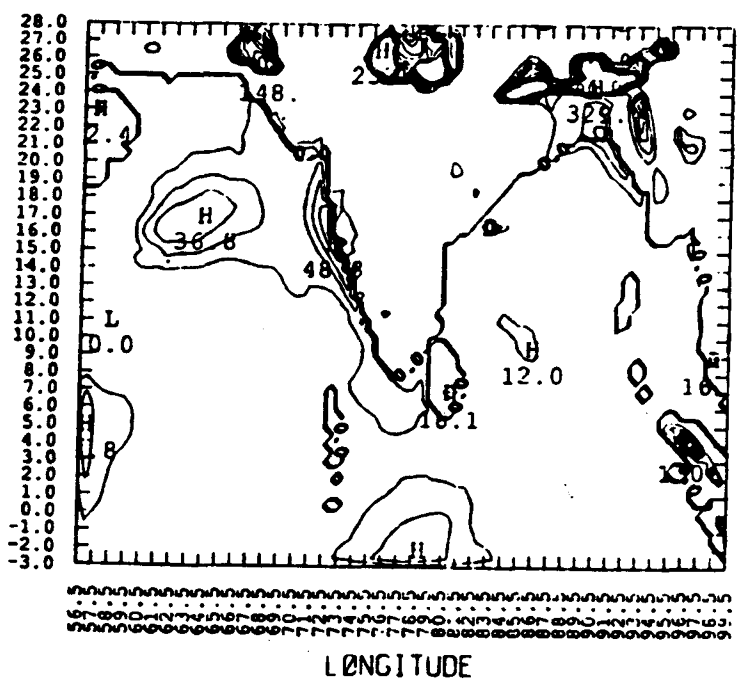

Fig. 9. Total rainfall (mm/day) predicted by the FM model during the second 24 hours of simulation

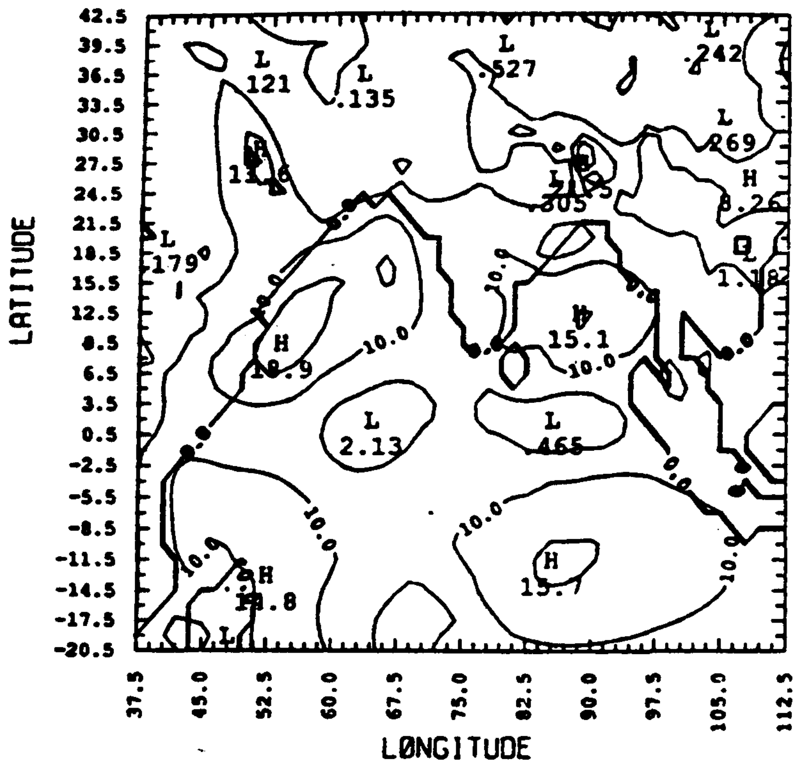

Fig. 10. Predicted wind speed by the CM model at the end of the 24 hour simulation (June 25, 1979; 00 GMT)

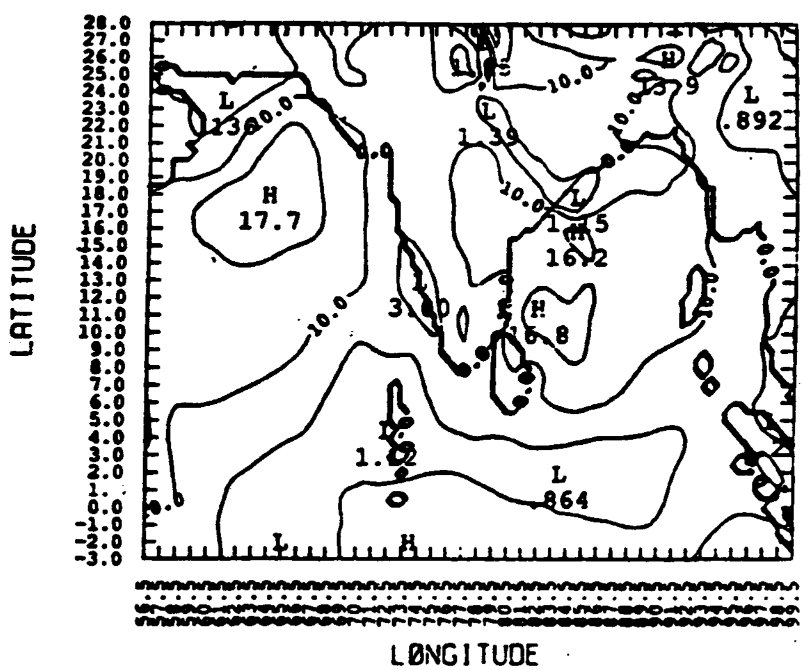

Fig. 11. Predicted wind speed by the FM model at the end of the 24 hour simulation (June 25, 1979; 00 GMT)

wind surge over Arabian sea is about 20 mm/day. Rainfall maximum over Ghat mountain region predicted by the FM model is about 48 mm/day (Fig. 9) and is located just offshore and rainfall due to the wind surge is about 36 mm/day. Rainfall maximum over this region (Arabian sea) has moved 4 degrees of longitude in 24 hours which can be again related to the movement of wind surge moving at the same speed. The spatial distribution of rainfall over ghat mountain region in FM domain is closer to the observation than that in CM domain. During the second day predicted monsoon depression has weakened with a significant reduction in predicted rainfall.

4. CONCLUSIONS

A limited area nested grid model is used to simulate the rainfall over the Western Ghat mountain region during the Indian southwest monsoon. Model simulations are done for 48 hours for both Fine and Coarse Grid networks. It is found that the grid resolution plays an important role in the numerical simulations. A monsoon depression which existed during the period of simulation is better simulated by the FM model than by the CM model. Also the spatial and temporal distribution of the rainfall over the domain is better simulated by the FM model than CM model. The representation of the mountains in a coarse grid network leads to spurious rainfall over the lee side of the mountains.

ACKNOWLEDGEMENTS

This work was supported by the Naval Research Laboratory, Washington, D.C. Part of the computer time was provided by the North Carolina Supercomputing Centre, Research Triangle Park, N.C.

REFERENCES

Anthes, R.A., 1977: Hurricane Model experiments with a new cumulus parameterization scheme. *Mon. Wea. Rev.*, **105**, 287-300.

Grossman, R.L., and D.R. Durran, 1984: Interaction of low-level flow with the Western Ghat Mountains and offshore convection in the summer monsoon. *Mon. Wea. Rev.*, **112**, 652-672.

Krishnamurti, T.N., S. Cocke, R. Pasch and S. Low-Nam, 1983: Precipitation estimates from rainguage and satellite observations: Summer MONEX. Dept. of Meteorology, Florida State University, 377 pp.

Kuo, H.L., 1974: Further studies of the parameterization of the influence of cumulus convection on large-scale flow. *J. Atmos. Sci.*, **31**, 1232-1240.

Perkey, D.J. and C.W. Kreitzberg, 1976: A time-dependent lateral boundary scheme for limited-area primitive equation models. *Mon. Wea. Rev.*, **104**, 744-755.

Ramachandran, G., 1972: The role of orography on wind and rainfall distribution in and around a mountain gap: Observational study. *Indian J. Metero. Geophys.*, **23**, 41-44.

Ramakrishnan, K.P., and B. Gopinatha Rao, 1958: Some aspects of the nondepressional rain in peninsular India during the southwest monsoon. *Proc., Symp on the Monsoon World*, India Meteorological Department.

Smith, R.B., and Y.-L. Lin, 1983: Orographic rain on the western Ghat. *Proc., First Sine-American Workshop on Mountain Meteorology*, E.R. Reiter, Z. Baozhen and Q. Youngfu, Eds., 71-94.

Yoshi Ogura and Masanori Yoshizaki, 1988: Numerical Study of Orographic-Convective Precipitation over the Eastern Arabian sea and the Ghat Mountains during the Summer Monsoon. *J. Atmos. Sci.*, 45, 2097-2122.

Young, J.A., H. Virji, D.P. Wylie and C. Lo, 1980: Summer monsoon windsets from geostationary satellite data, 1 May-31 July 1979. Space Science and Engineering Center, University of Wisconsin, 125 pp.