

Numerical Simulation of Indian Southwest Monsoon Rainfall using Kuo and Betts Cumulus Parameterization schemes

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1. INTRODUCTION

Cumulus convection is one of the processes that plays an important role influencing the dynamic and thermodynamic state of the atmosphere. Numerical simulation experiments can be performed via explicit or implicit treatment of the convective processes with or without an in-depth representation of the physical processes involved during convection. Since the convective elements are normally of the size of 0.1 to 1 km, fine resolution is required in numerical models for an explicit treatment of the convective processes. On the other hand, parameterization schemes allow us to use coarser grid in numerical simulations where the horizontal scale of the phenomena is of the order of several thousands of kilometers. Cumulus parameterization schemes currently being used in large- and meso-scale models can be categorized into three groups: the moisture convergence scheme (Kuo, 1965, 1974), the heat and moisture budget scheme (Arakawa and Schubert, 1974) and the moist convective adjustment scheme (Manabe *et al.*, 1965).

Because of its simplicity and ease of implementation in numerical models compared to other schemes, Kuo scheme is widely used in research and operational models. The essence of the Kuo scheme is that the cumulus convection takes place in deep layers of conditionally unstable atmosphere and cumulus clouds generated dissolve instantaneously through later mixing with the environment, thereby imparting the heat and moisture carried by cloud air to the environment. The temperature and mixing ratio inside the cloud are considered as those on a moist adiabat passing through lifting condensation level of an air parcel near surface. Here the parcel is lifted moist adiabatically

though the reversible processes reduce its buoyancy due to the presence of the condensate. It has been shown that tropical atmosphere is less unstable or nearly neutral (Rotunno and Emanuel, 1987). Hence if we lift the air parcel along a moist adiabat without accounting for the reversible processes, the resultant condensation should eventually dry the atmosphere. Since Kuo scheme is moisture convergence scheme, moisture partitioning is one of the problems of the Kuo scheme and several methods have been proposed to alleviate it (Anthes, 1977a; Gelyen, 1985). Semi-prognostic studies during the summer monsoon period by Someshwar Das *et al.*, (1988) using several versions of Kuo scheme showed that Kuo (1974) scheme provided considerable improvement in simulating the heating, drying and rainfall rates. They also noticed that the choice of small (almost equal to zero) moistening parameter can cause unrealistic drying of the atmosphere.

Based on the observations that the tropical atmosphere does not approach a moist adiabatic equilibrium state in the presence of deep convection, Betts (1986) proposed a new convective adjustment scheme which relaxes the thermodynamic profiles of the atmosphere towards observed state. This scheme has been slightly modified (e.g., stability weight on mixing line slope, cloud top in shallow and deep convective regimes and cloud base) by Baik *et al.*, (1990a) and was tested in axi-symmetric tropical cyclone model. Sensitivity tests were performed using the Betts scheme by Baik *et al.* (1990b) showing that the Betts scheme is capable of simulating the model tropical cyclone successfully.

Convective rainfall is predominant during the southwest monsoon season over the Indian subcontinent region. One of the regions which receives large rainfall is the west coast of India where the Ghat mountains run parallel to the west coast at about 50 km inland. Analytical and numerical studies [e.g., Smith and Lin (1983), Grossman and Durran (1984), Ogura and Yoshizaki (1988)] show that the Ghat mountains supply orographic lifting to the air parcels and the prevailing convective instability can trigger deep convection. The objective of the present study is to simulate the spatial and temporal distribution of rainfall over the Indian monsoon region using Kuo (1974) scheme and Betts scheme modified by Baik *et al.* (1990a) using a limited area nested grid model.

2. DESCRIPTION OF THE MODEL AND CUMULUS PARAMETERIZATION SCHEMES

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 and fast moving gravity modes. For horizontal differencing a staggered grid net-

work (Arakawa's C-grid) is used. The FM grid is nested into the CM grid such that every third FM grid is collocated 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. Lateral boundary conditions suggested by Perkey and Kreitzberg (1976) are employed in the present version of the model.

Bulk aerodynamic formulae are used to determine the surface transfer of momentum, sensible heat and latent heat. Cumulus convection parameterization schemes used in this model is either the one suggested by Kuo (1974) and modified by Anthes (1977) or the one suggested by Betts (1986). If supersaturation 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.

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 were used to interpolate to model grid points at 10 levels. Bicubic polynomial interpolation is used for horizontal fields and appropriate profiles are 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. FM domain covers from 30° E to 120° E and 28° S to 50° N and CM domain from 54° E to 102° E and 5.5° S to 30.5° N. Model integrations are carried out for 48 hours starting from 00Z June 24, 1979. Model grid topography for FM and CM domains were obtained from Navy 10 minute global topography data. The difference between the peaks of the Ghat mountains in FM and CM domains is about 285 m. A nonlinear normal mode initialization technique similar to that suggested by Bourke and McGregor (1983) is employed.

2.1 Kuo and Betts cumulus parameterization schemes

In 1965, Kuo proposed a parameterization scheme to account for the effects of cumulus convection and resulting changes in the large-scale humidity and temperature distributions. He assumed cumulus convection to occur in deep layers of conditionally unstable atmosphere with the base of the cloud at the level of condensation. The vertical distribution of temperature and mixing ratio within the cloud are assumed as those of a moist adiabat and the top of the cloud is defined as the level where the moist adiabat crosses the environmental sounding. Cumulus clouds are assumed to dissolve immediately by mixing with the environmental air imparting heat and moisture. Kuo assumed that the total rate of moisture accession per unit horizontal area as the sum of the convergent moisture in a column of air above the unit area and evaporation from the surface. Then the cumulus heating and drying imparted to the environment is

assumed to be proportional to the temperature and water vapor mixing ratio differences between the environment and the cloud.

In 1986, Betts proposed a convective adjustment scheme based on the observations in the tropical atmosphere. In essence, the Betts scheme relaxes the thermodynamic structure of the atmosphere towards the observed quasi-equilibrium state. The present version of the Betts scheme contains shallow as well as deep convection. Since Kuo scheme deals with the deep convection we employ only deep convection part of the Betts scheme in this part for comparison and shallow convection is ignored. A crucial observational basis for the Betts deep convection scheme is that a quasi-equilibrium temperature profile below the freezing level closely parallels a moist virtual adiabat and the use of moist virtual adiabat allows for a parcel buoyancy correction due to the condensate. First guess of the vertical reference profiles are constructed based on the conservation of the moist static energy. The stability weight on the moist adiabat in the lower troposphere is internally computed assuming that the reference temperature profile below the freezing level follows a moist virtual adiabat. For further details regarding Betts scheme reader is referred to Baik *et al.* (1990).

3. DISCUSSION OF RESULTS

A numerical experiment is performed using the FGGE data at 00 GMT June 24, 1979 and numerical integration is carried out for 48 hours. There are $61 \times 53 \times 10$ and $97 \times 73 \times 10$ grid points in the Coarse Mesh (CM) and Fine Mesh (FM) domains with 1.5° and 0.5° horizontal resolution respectively. Monsoon depressions occur over the Bay of Bengal during the southwest monsoon season and generally travel in a north-northwesterly direction. During the period of simulation a monsoon depression was present within the model domain and is also simulated by both CM and FM models. Coasts in both CM and FM domains were determined based on the topography data and thick solid lines in all figures represent the coastal lines.

Figures 1 and 2 show the analyzed rainfall by Krishnamurti *et al.* (1983). The maximum rainfall over the western ghat region during the period of simulation is about 169 mm/day with a considerable spatial variation. A monsoon depression was located over the eastern part of India close to the Bay of Bengal with a rainfall maximum of about 160 mm/day for the period ending at 00 GMT of June 25, 1979 (Fig. 1). During the second day (Fig. 2) this depression weakened and moved over the central part of the Indian subcontinent. Rainfall maximum over the western coast region was about 155 mm/day for the period ending at 00 GMT of June 26, 1979. During both the days the maximum rainfall was located just offshore but not inland. Figures 3 and 4 show the predicted rainfall by the FM model using Kuo and Betts schemes respectively for the 24 hour period ending at 00 GMT of June 25, 1979. Predicted rainfall maximum using Kuo scheme along the west coast of India is about 20 mm/day and the rainfall

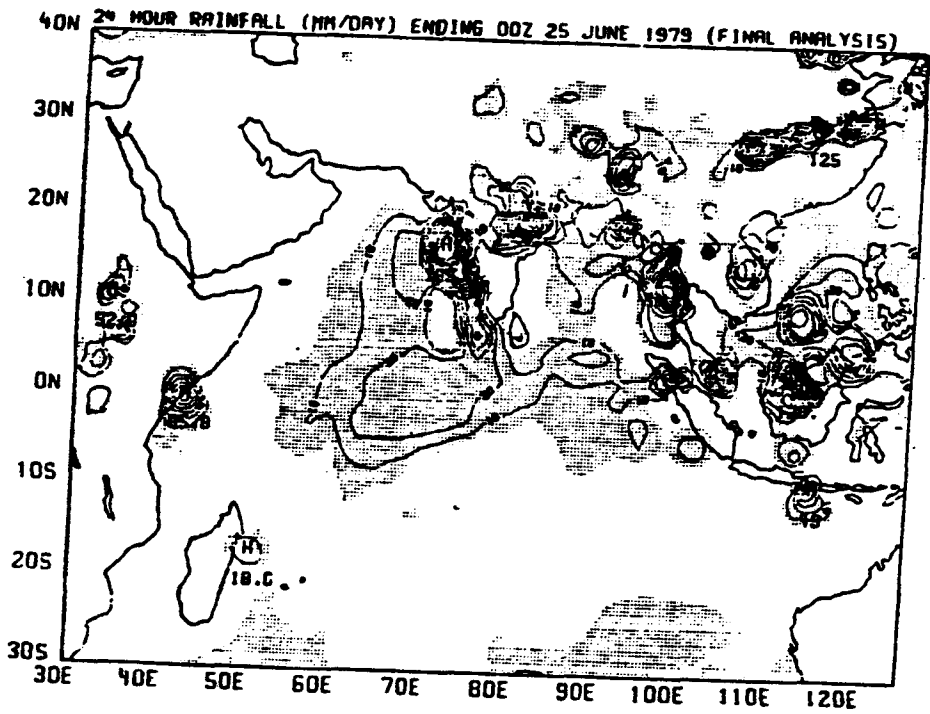


Fig. 1. Analyzed Rainfall distribution (mm/day) ending at 00 GMT of June 25, 1979. Large rainfall can be seen along the west coast of India, northeastern part of India and Burma coast.

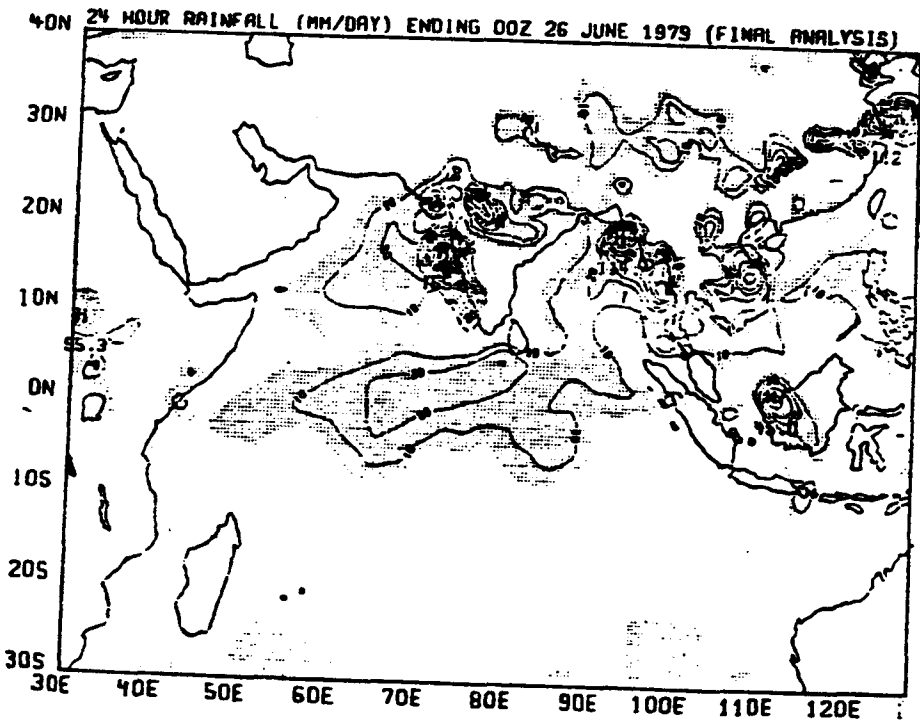


Fig. 2. Analyzed Rainfall distribution (mm/day) ending at 00 GMT of June 26, 1979.

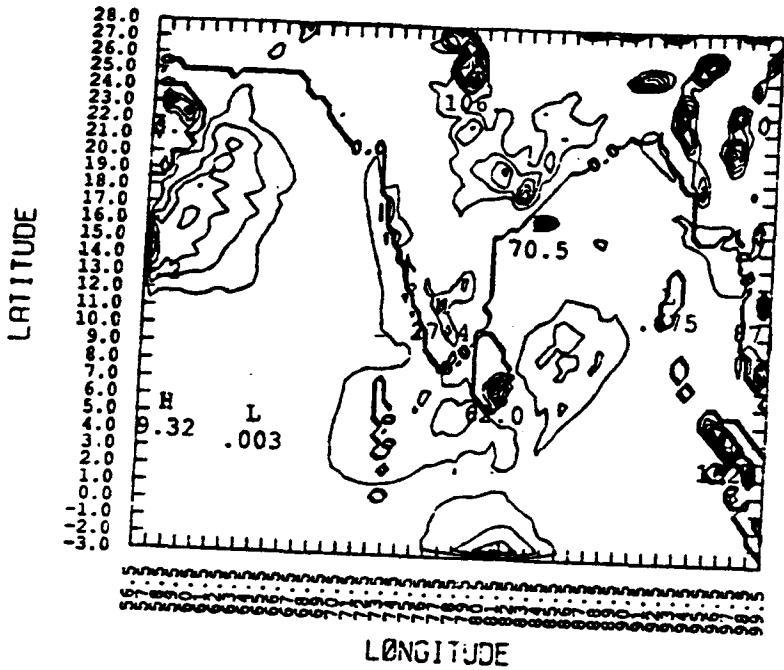


Fig. 3. Model predicted rainfall (mm/day) at the end of the 24 hour simulation ending at 00 GMT of June 25, 1979 using Kuo scheme. Contour interval: 10 mm.

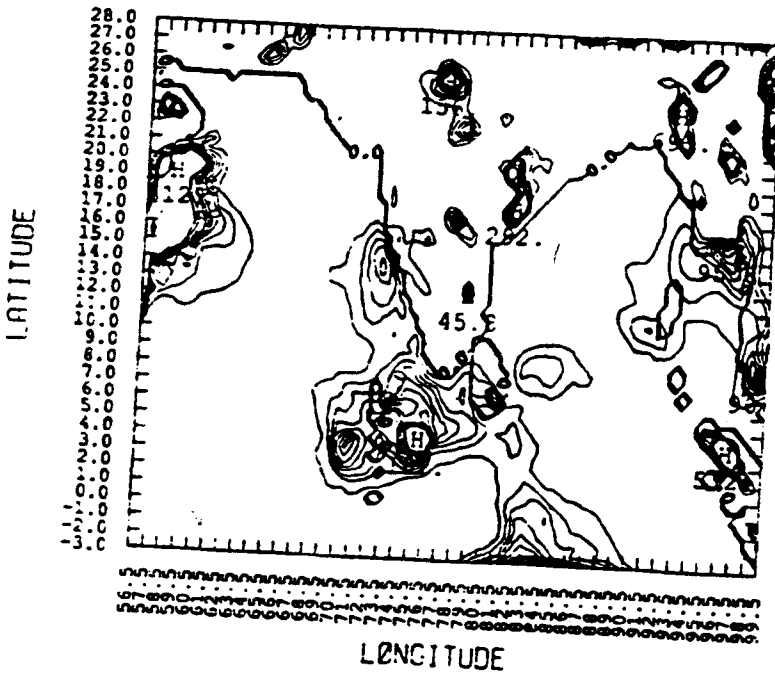


Fig. 4. Model predicted rainfall (mm/day) at the end of the 24 hour simulation ending at 00 GMT of June 25, 1979 using Betts scheme. Contour interval: 10 mm.

maximum due to the monsoon depression is about 50 mm/day. Predicted rainfall maximum by the FM model using Betts scheme along the west coast is about 50 mm/day and is located off shore. Predicted rainfall due to the monsoon depression is about 292 mm/day while the observed maximum is about 160 mm/day for the same period.

Rainfall over the western part of the Arabian sea was due to the presence of a wind surge which travelled eastward. Satellite cloud pictures also show some cloudiness over this region and Betts scheme gave larger rainfall over this region compared to the Kuo scheme. Observations show large rainfall over the Burma coast and the rainfall maximum over this region was about 90 mm/day. Kuo scheme gave very little precipitation whereas Betts scheme gave about 95 mm/day over this region.

Kuo scheme depends on the moisture convergence in the boundary layer and if the divergence field in the model is weak Kuo scheme may give low convective rainfall. Each model has a finite spin-up time and the predicted convective rainfall is generally small during the period of spin-up. On the other hand, in the Betts scheme (hereafter referred to as B-case) the amount of convective rainfall depends on the extent of the deviation of the atmospheric thermodynamic structure from the quasi-equilibrium state.

Rainfall predictions using Kuo and Betts schemes for the second day of simulation (ending 00 GMT of June 26, 1979) are shown in Figs. 5 and 6 respectively. During the second day of simulation Kuo scheme (hereafter referred to as K-case) gave small (less than 10 mm/day) rainfall over the monsoon depression region but in the B-case predicted rainfall is large (about 279 mm/day). On the other hand analyzed rainfall along the west coast of the India (Fig. 2) is about 155 mm/day (ending 00 GMT June 26, 1979) and the predicted rainfalls over this region using Kuo and Betts schemes are about 48 and 106 mm/day respectively with the maximum located just offshore. The spatial distribution of the rainfall predicted in the B-case is much closer to the observed one than the one for the K-case. However, the wind surge moved eastward and was better simulated in the K-case; in the B-case it has intensified and remained stationary. Large rainfall in the B-case near Sri Lanka region is due to strong convergence of the wind in the B-case. In the K-case the convergence is weak over this region. Observations indicate about 30 mm/day rainfall in this area (Fig. 2). In the K-case large rainfall was predicted over the northern parts of the domain where mountains are present.

Figures 7 and 8 show the vertical velocity field (cm/s) at the lowest level in the model ($\sigma = 1.0$) for the FM domain for the K-case and B-case respectively at 00 GMT of June 25, 1979 and negative values indicate rising motion. Rising motion along the west coast of India is weaker (3.3 cm/s) in K-case than in the B-case (6.1 cm/s). Sinking motion on the lee side of the Ghat mountains is also relatively weaker in the K-case (3.6 cm/s) than in the B-case (4.5 cm/s). The monsoon depression was located over the eastern part of India at 00 GMT of

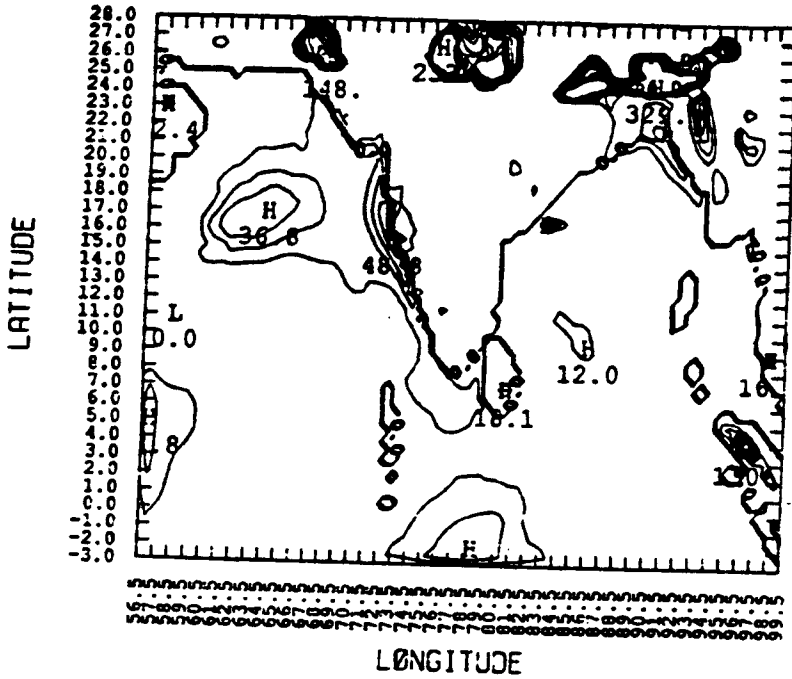


Fig. 5. Model predicted rainfall (mm/day) for the second day of simulation ending at 00 GMT of June 26, 1979 using Kuo scheme. Contour interval: 10 mm.

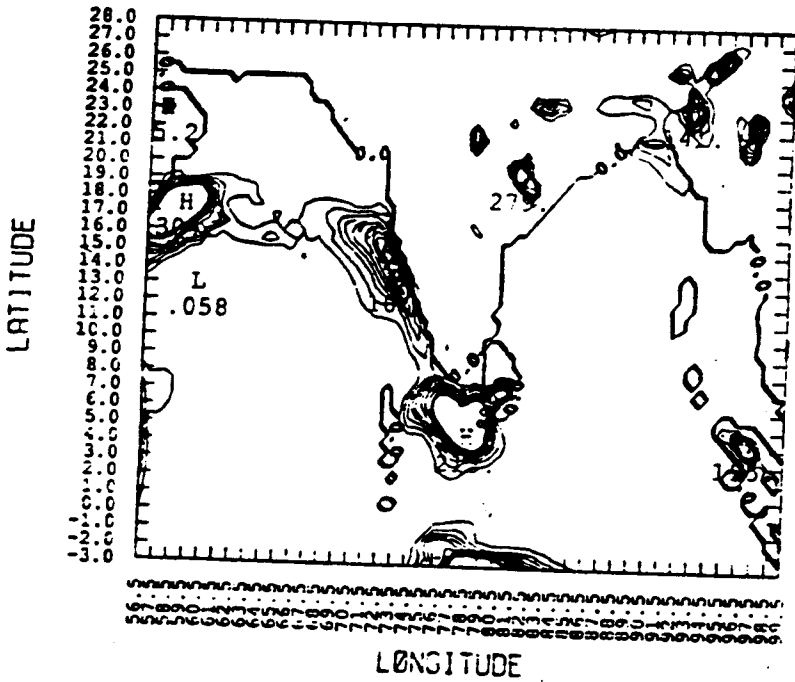


Fig. 6. Model predicted rainfall (mm/day) for the second day of simulation ending at 00 GMT of June 26, 1979 using Betts scheme. Contour interval: 10 mm.

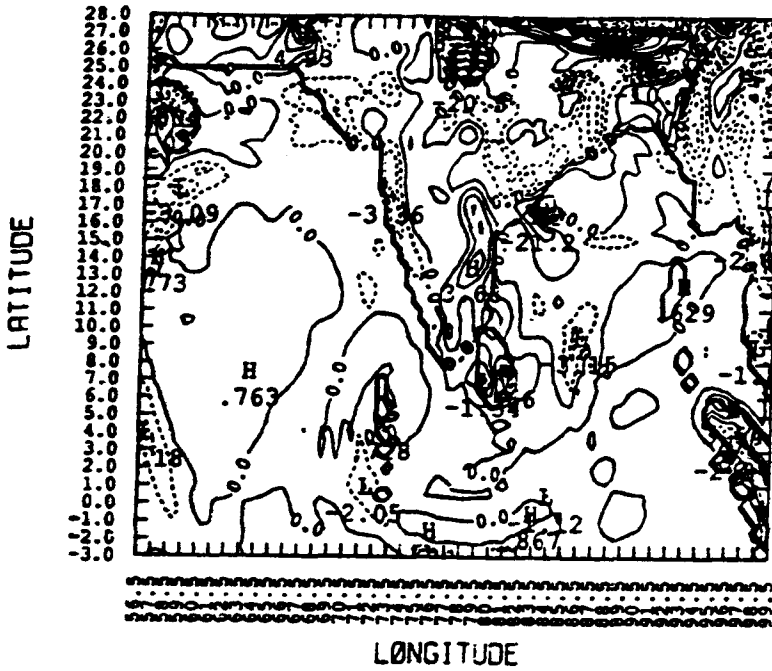


Fig. 7. Vertical velocity field in cm/s at the lowest level of the model ($\sigma = 1.0$) at 00 GMT of June 25, 1979 for the model simulation using Kuo scheme. Contour Interval: 1 cm/s.

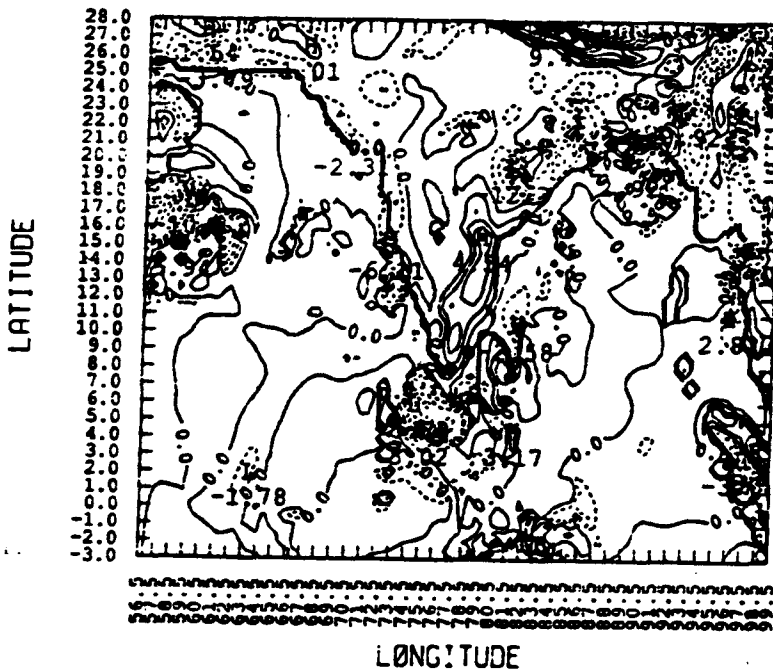


Fig. 8. Vertical velocity field in cm/s at the lowest level of the model ($\sigma = 1.0$) at 00 GMT of June 25, 1979 for the model simulation using Betts scheme. Contour interval: 1 cm/s.

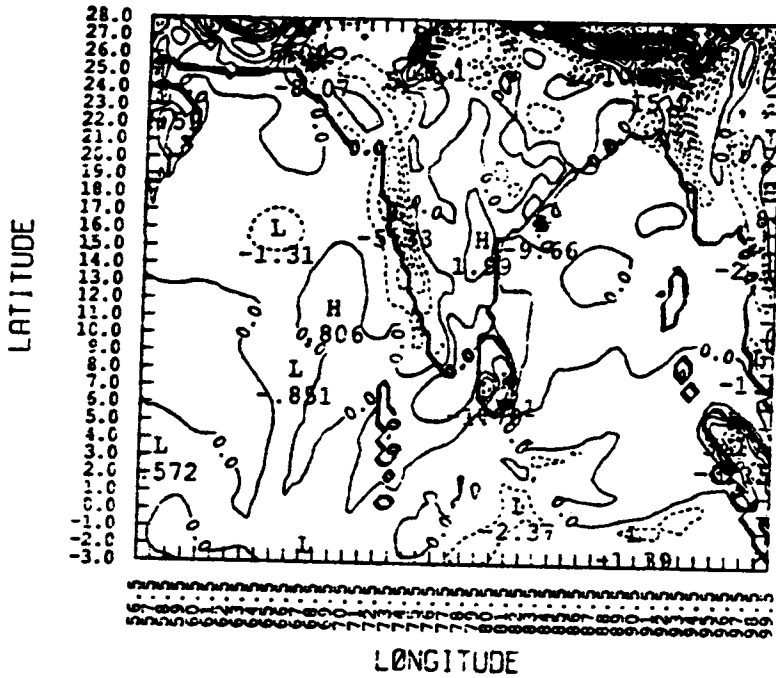


Fig. 9. Vertical velocity field in cm/s at the lowest level of the model ($\sigma = 1.0$) at 00 GMT of June 26, 1979 for the model simulation using Kuo scheme. Contour interval: 1 cm/s.

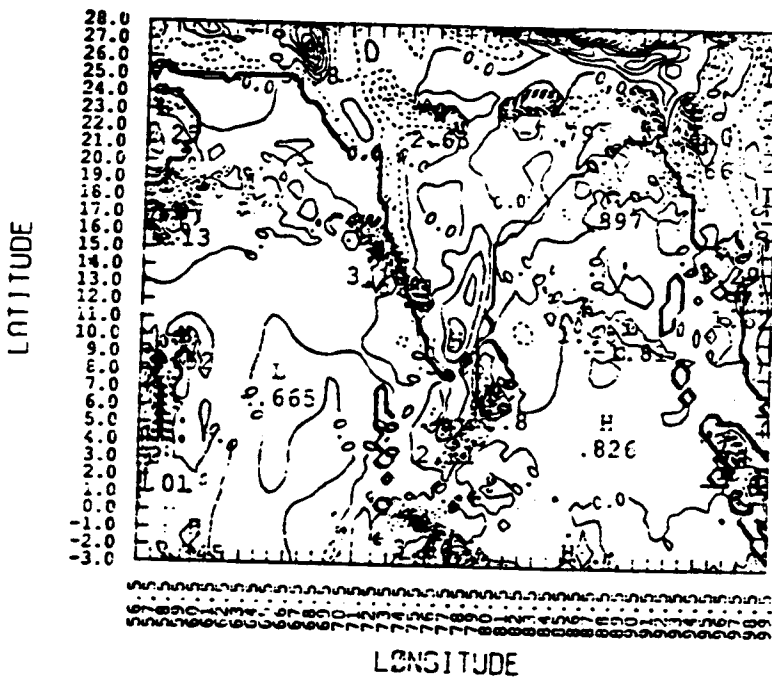


Fig. 10. Vertical velocity field in cm/s at the lowest level of the model ($\sigma = 1.0$) at 00 GMT of June 26, 1979 for the model simulation using Betts scheme. Contour interval: 1 cm/s.

June 25, 1979. Vertical velocities over this region are larger in the B-case (12.3 cm/s) than in the K-case (3 cm/s). In the K-case, along the west coast there is negligible rising motion offshore compared to the B-case. Observations indicate that the rainfall maximum to be located not over the mountains but offshore. Figures 9 and 10 show the vertical velocity field (cm/s) at the lowest level of the FM model for the K-case and B-case respectively at 00 GMT of June 26, 1979. During this period in the K-case rising motion offshore is weak (1 cm/s) but is pronounced over the mountain region. In the B-case rising motion can be seen offshore with a maximum of 6.3 cm/s. The rising motion over central Arabian sea is believed to be due to the wind surge and is about 1.3 cm/s in the K-case. In the B-case the wind surge was still located over the western Arabian sea with little movement.

4. CONCLUSIONS

A ten layer primitive equation model is used to simulate the rainfall distribution over the Indian southwest monsoon region using two different cumulus parameterization schemes. Results indicate that the model predictions show considerable improvement in predicting rainfall when Betts cumulus parameterization is used. The magnitude of the predicted rainfall using Kuo scheme was less compared to the Betts scheme but both schemes under-predict the rainfall over the Ghat mountain region. The differences in the dynamic fields in the both cases show the influence of the cumulus convection on the large-scale flow and also the effect of the representation of the convective process. Currently we are testing the Betts scheme with different relaxation time values and with specification of different values of the saturation pressure departure at the surface level. The Betts scheme used in this study may have parameters suitable for tropical cyclone simulation. It would be interesting to determine the validity of these parameters for the monsoon circulation where the thermodynamic processes are some what different.

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