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APPLICATION OF A QUASI-LAGRANGIAN REGIONAL MODEL FOR MONSOON PREDICTION

BY

S.S. SINGH.

AND

A. BANDYOPADHYAY.

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Application of a Quasi-Lagrangian regional model for monsoon prediction

S.S. Singh and A. Bandyopadhyay

Indian Institute of Tropical Meteorology, Pune-8, India

Abstract

A quasi-Lagrangian regional primitive equation model is applied for prediction of monsoon depression. The model has ten levels in vertical and the domain extends from 10°S to 40°N and 40°E to 120°E. The domain is resolved into 250 km grid on Mercator projection. The physical processes included are : the surface friction, sensible and latent heat fluxes from the sea surface, large scale condensation and Kuo convection. The model has been integrated upto 48 hrs using time invariant lateral boundary condition. The forecast results are found satisfactory upto 24 hr and beyond that deteriorate rapidly. Spurious growth of short-wave is noticed near the northern boundary. The appearance of noise may be due to the high truncation error in evaluating the pressure gradient force near the Himalayan region.

1. Introduction

One of the objectives of Indo-US STI on monsoon research was to formulate and test a regional primitive equation model for weather forecast over Indian region. Under this bilateral programme, a quasi-Lagrangian regional primitive equation model for the prediction of meso-scale and synoptic scale disturbances was made available to the Institute from National Meteorological Centre, USA (Mathur, 1983). The two noteworthy features of the model are (i) the model can be integrated over any geographical area and with any horizontal and vertical resolutions and (ii) the parameterization of physical processes could be varied without much alteration of the code.

The model has been tested for investigating its application potential for monsoon prediction. The report briefly presents the chief features of the model, the physical processes, the experiments carried out and the results obtained.

2. Model equations

The model equations are in sigma coordinate on Mercator projection and are in advection form. Sigma (σ) is defined as

$$\sigma = \frac{p}{p_s}$$

where p is pressure at any level and p_s denotes the pressure at the lower boundary. The set of equations are:

Momentum equations

$$\frac{Du}{Dt} = A = \left[f + v\frac{\partial m}{\partial x} - u\frac{\partial m}{\partial y}\right]v - \dot{\sigma}\frac{\partial u}{\partial \sigma} - m\frac{\partial \Phi}{\partial x} - mC_p\theta\frac{\partial \pi}{\partial x} + F_{u\sigma}$$

$$\frac{Dv}{Dt} = B = -\left[f + v\frac{\partial m}{\partial x} - u\frac{\partial m}{\partial y}\right]u - \dot{\sigma}\frac{\partial v}{\partial \sigma} - m\frac{\partial \Phi}{\partial y} - mC_p\theta\frac{\partial \pi}{\partial y} + F_{v\sigma}$$

Thermodynamic equation

$$\frac{D\theta}{Dt} = C = -\dot{\sigma}\frac{\partial \theta}{\partial \sigma} + \frac{\theta}{C_p T}H + F_{\theta\sigma}$$

Moisture continuity equation

$$\frac{Dq}{Dt} = D = -\dot{\sigma}\frac{\partial q}{\partial \sigma} + M + F_{q\sigma}$$

Continuity equation

$$\frac{D(\ln p_s)}{Dt} = E = -\nabla_\sigma \cdot \vec{V} - \frac{\partial \dot{\sigma}}{\partial \sigma}$$

Hydrostatic equation

$$\frac{\partial \Phi}{\partial \sigma} = -\frac{RT}{\sigma} = -C_p \theta \frac{\partial \pi}{\partial \sigma}$$

where u and v are horizontal components of wind, θ the potential temperature, q the humidity mixing ratio, Φ the geopotential, $\dot{\sigma}$ the vertical velocity, T the temperature, C_p the specific heat at constant pressure, R the gas constant for dry air, H the rate of heating per unit mass, M the change in mixing ratio due to convection, $\vec{V}$ the horizontal wind vector, m the map factor and

$$\pi = \frac{T}{\theta} = \left(\frac{p}{1000}\right)^{R/C_p}$$

the Poisson equation,

$F_{u\sigma}$, $F_{v\sigma}$, $F_{\theta\sigma}$ and $F_{q\sigma}$ represent the vertical exchange of momentum, heat and moisture respectively due to sub-grid scale processes.

3. Vertical structure

The vertical structure of the model is shown in Fig.1. Although any number of layers can be used, a minimum of ten layer is considered necessary for obtining positive impact on forecast of the physical processes included in the model. In horizontal, variables are defined at all grid points and in vertical, variables are evaluated in layers. Upper boundary of the model is at the level where pressure is zero and the lower boundary is the earth-surface. $\sigma = 1$ and $\sigma = 0$ are set at the lower and upper boundary of the model respectively. The values of σ at the interfaces of ten layers are 0.95, 0.90, 0.80, 0.60, 0.40, 0.325, 0.250, 0.175 and 0.10.

4. Time-step, boundary conditions, finite-difference scheme and time integration scheme

A time-step of 5 minutes is used to integrate the model using a time-invariant lateral boundary condition.

In vertical $\dot{\sigma} = 0$ both at the lower and upper boundary. Space derivatives are approximated by second order centred difference scheme.

A one-step second order quasi-Lagrangian advective scheme (Mathur, 1983) is used to integrate the model. A special feature of the scheme is that it takes into account the changes in acceleration of dependent variables and advecting velocity over the trajectory traced by the parcel in each time-step. The non-linear advective terms and total forcing experienced by the parcels are therefore evaluated with high degree of accuracy.

It has been shown by Mathur (1970) that in a semi-Lagrangian primitive equation barotropic model, mean total energy and mean square potential vorticity were nearly conserved even after 7-days of integration. In the multi-level model, the mass conservation could be ensured using consistent boundary condition. The accuracy of the semi-Lagrangian scheme is equivalent to that of fourth order schemes (Krishnamurti et al., 1973).

The semi-Lagrangian scheme used in the present study is briefly outlined here, Advective distances $\xi_{i,j}$ and $\eta_{i,j}$ at a grid point (i, j) are obtained from the relations

$$\xi^{n}_{i,j} = \left[\left(I - G'\right)\left(I - H'\right)X\right]_{i,j}$$

$$\eta^{n}_{i,j} = \left[\left(I - G'\right)\left(I - H'\right)Y\right]_{i,j}$$

where

$$X_{i,j} = u^{n}_{i,j}\,\Delta t + A^{n}_{i,j}\,\frac{\Delta t^2}{2}$$

$$Y_{i,j} = v^{n}_{i,j}\,\Delta t + B^{n}_{i,j}\,\frac{\Delta t^2}{2}$$

$$G' = X_{i,j}\,\frac{\partial}{\partial x} - \frac{X^2_{i,j}}{2!}\,\frac{\partial^2}{\partial x^2}$$

$$H' = Y_{i,j}\,\frac{\partial}{\partial y} - \frac{Y^2_{i,j}}{2!}\,\frac{\partial^2}{\partial y^2}$$

Once $\xi^n_{i,j}$ and $\eta^n_{i,j}$ are known, the predicted value of a variable F after a time-step Δt is obtained as

$$F^{n+1}_{i,j} = \left[(I-G)(I-H)W\right]_{i,j} - \left(R^n_{i,j} - 0.5\,R^{n-1}_{i,j}\right)\Delta t$$

where

$$W_{i,j} = F^n_{i,j} + \frac{\Delta t}{2} R^n_{i,j}$$

$$(IW)_{i,j} = W_{i,j}$$

$$R^n_{i,j} = \frac{DF^n_{i,j}}{Dt}$$

$F^n_{i,j}$ is the value of any one of the variables u, v, θ or q at any level K

$$G = \xi^n_{i,j}\frac{\partial}{\partial x} - \frac{(\xi^n_{i,j})^2}{2!}\frac{\partial^2}{\partial x^2}$$

$$H = \eta^n_{i,j}\frac{\partial}{\partial y} - \frac{(\eta^n_{i,j})^2}{2!}\frac{\partial^2}{\partial y^2}$$

The superscript n is used for time level and i, j are the horizontal space indices in X and Y direction respectively.

The prediction equation for surface pressure is

$$p_S^{n+1} = \sum_{K=1}^{L} \Delta\sigma_K \left\{ \left[(I-G)(I-H)Z \right]_{i,j} - p_S^{n} \left(\nabla_\sigma \cdot \vec{V} \right)_{i,j}^{n+1} \frac{\Delta t}{2} \right\}$$

where

$$Z_{i,j} = \left[p_S^{n} - p_S^{n} \left(\nabla_\sigma \cdot \vec{V} + \frac{\partial \dot{\sigma}}{\partial \sigma} \right)^{n} \frac{\Delta t}{2} \right]_{i,j}$$

and L is the number of Layers.

The predicted value of $\dot{\sigma}$ (vertical velocity) is evaluated at each level K starting from the topmost layer from the relation

$$\dot{\sigma}_K^{n+1} = \dot{\sigma}_{K+1}^{n+1} - \frac{\Delta\sigma_K}{p_S^{n} \frac{\Delta t}{2}} \left[p_S^{n+1} - \left\{ (I-G)(I-H)Z \right\}_{i,j} - p_S^{n} \left(\nabla_\sigma \cdot \vec{V} \right)_{i,j}^{n+1} \frac{\Delta t}{2} \right]_K$$

5. The physical processes

The physical processes included in the model are :

i) Exchange of momentum between the surface and overlying atmosphere. The drag-coefficient is made to vary with wind speed.

ii) Vertical eddy transport of sensible heat and moisture from the sea-surface. Bulk formulas are used to compute the fluxes.

iii) Large-scale condensation is evaluated at the super-saturated grid point at the end of each time-step. The temperature and mixing ratio are adjusted so that the relative humidity has the value close to 100%. If humidity mixing ratio becomes negative at any point, it is set zero.

iv) A Kuo (1965) type parameterization scheme is employed to compute the convective transfer of heat and moisture. The convective cloud is assumed to develop from the lifting condensation level (LCL). The cloud parcel is allowed to originate from one of the three layers next to the ground. The criteria for building up convective cloud is that the parcel should be warmer than the environment at least in two adjacent layers above the parcel's LCL. If the parcel originating from the lowest layer does not build a model convective cloud, the clouds are built with the parcels originating in the next layer and so on.

v) The model uses horizontal diffusion to parameterize the sub-grid scale horizontal diffusion and for noise control.

6. Data and grid

The area of integration extends from 10°S to 40°N and from 40°E to 120°E. The horizontal area of the domain is resolved into uniform grid of 250 km grid-size on Mercator projection. The number of grid points in zonal and meridional directions are 33 and 23 respectively. Input data are prepared from globally analysed 15 pressure levels FGGE IIIb data set of 12 GMT, 7 July, 1979, when the dominant synoptic situation is a monsoon depression. The pressure levels are 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10 mb. The data at sigma levels are interpolated from the data of these 15 pressure levels.

The interpolation is done linearly on Log p scale where p is pressure. As far as possible, it is ensured that each sigma level lies between the two pressure levels. However, in case of a grid point on sigma surface falls above 10 mb or below 1000 mb pressure levels, the wind and humidity of the nearest pressure level are set on the sigma surface. The temperature is obtained by extrapolating linearly on Log p scale using the values of temperature on two nearest pressure levels.

No initialization was done to obtain initial balance. The model is then integrated upto 48 hr. The forecast results in sigma surface are converted to desired standard pressure levels.

7. Forecast results

The model has been integrated upto 48 hrs. However, the results upto 24 hr only are presented as beyond that the forecast deteriorates rapidly. The results are evaluated by preparing the initial, forecast and corresponding verification charts of flow patterns at 850, 500 and 200 mb. The forecast and corresponding verification wind charts are given in Fig. 3 (a-c). The chief features of the forecast produced by the model are :

i) The model is stable and has produced satisfactory forecast of circulation features at 850, 500 and 200 mb.

ii) It is able to retain the cyclonic circulation around the centre of the depression at 850 and 500 mb levels. Both at 850 and 500 mb levels, the predicted westerlies to the south of the centre of the depression are found comparable with the actual. However, at both the levels, forecast movement of the depression is seen to be slower than the actual.

iii) Spurious growth of short-waves in the northern sector of the domain are noticed in the forecast wind at all the three levels : particularly at 850 and 500 mb levels. The appearance of this strong wave deteriorates the map-feature of the depression on the northern sector. The two-grid length wave also appears in surface pressure field (not presented). It is conjectured that this undesirable growth of short-waves may be due to the high orography (Himalayan region) near the northern boundary of the domain of integration.

In order to check the undesired growth of noise near the northern boundary, a few more experiments were carried out :

In one experiment, the domain of integration was extended further north so as to keep the northern boundary little further away from the Himalayas. The model was then integrated upto 24 hrs with a grid-size of 200 km. The forecast results of this experiment are presented in Fig.4 (a-c). It can be seen from Fig. 4(a-b) that at 850 and 500 mb levels the flow-pattern and the centre of cyclonic circulation associated with the depression are slightly better simulated by the model than in the earlier experiment when compared with the observed. The westerlies to the north of the centre of depression are also better simulated than earlier. But, spurious waves are still noticed in the wind field over the Himalayan region. The two-grid length oscillations in the surface pressure also continue to appear. At 200 mb level, no significant change in forecast wind field is noticed.

In another experiment, forecast results are obtained by applying strong divergent damping and also keeping tendencies of the variables within certain limit. No improvement could be noticed in the forecast field.

It is desirable to mention the performance of the model with reference to other two regional models viz. the six level P.E. model (Singh, et al, 1990) and the five level P.E. model (Singh, 1985) formulated and tested by our group. Although, we have not done statistical verification on the comparative performance of these models, based on synoptic verification it is inferred that the forecast produced by other two models are superior than that produced by the present model. As far as computational efficiency is concerned, the model requires 130 min CPU time on IITM-ND-560 computer for 24 hr forecast. The CPU time required for the present model, the six level P.E. model and the five level P.E. model are in the ratio of 3:7:2.

8. Concluding remarks

From the results of these limited number of experiments the follwing conclusions are drawn :

i) The quasi-lagrangian primitive equation model developed by Mathur (1983) is suitably modified and tested over Indian region for a case of monsoon depression.

ii) The model is stable and has produced satisfactory forecast of circulation features upto 24 hrs.

iii) Although the model has simulated the flow pattern of the cyclonic system fairly well, the westward movement of the system is not predicted very satisfactorily.

iv) Noise appears over the Himalayas. It is conjectured that the development of spurious wave is due to high truncation errors in the evaluation of pressure gradient force in the region of high orography.

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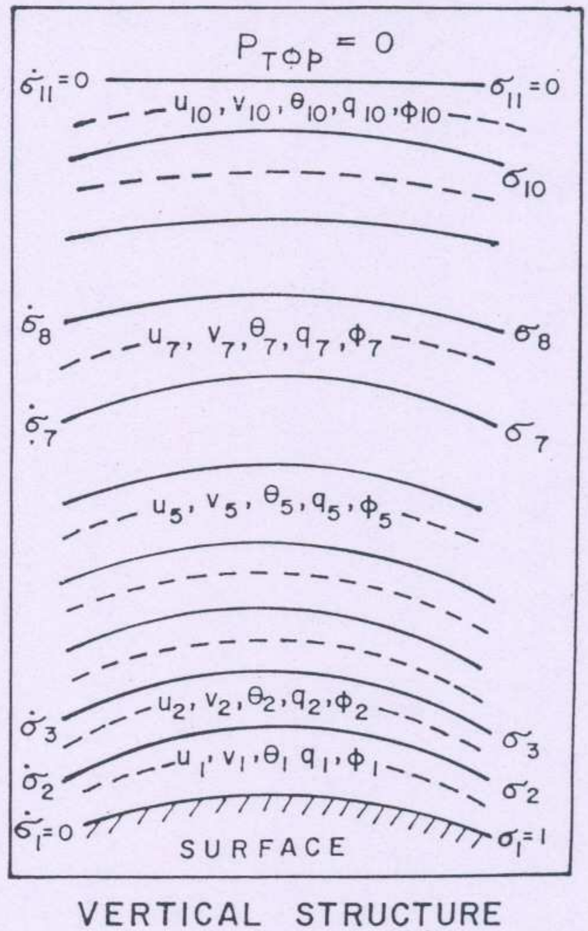


Fig. 1 : Vertical structure of the model

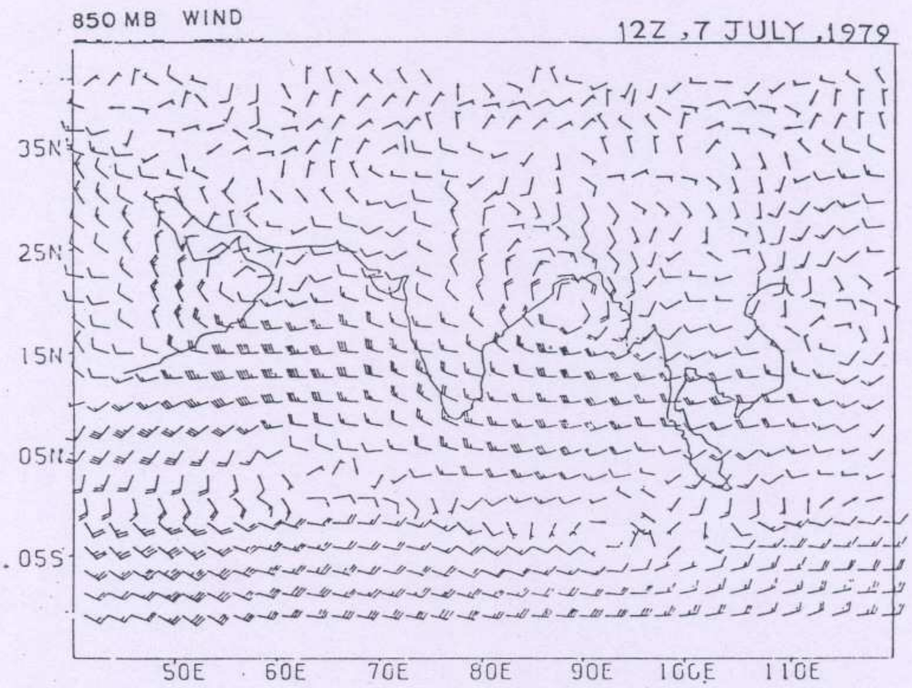


Fig. 2(a) : The initial wind charts at 850 mb level of 12 GMT, 7 July, 1979

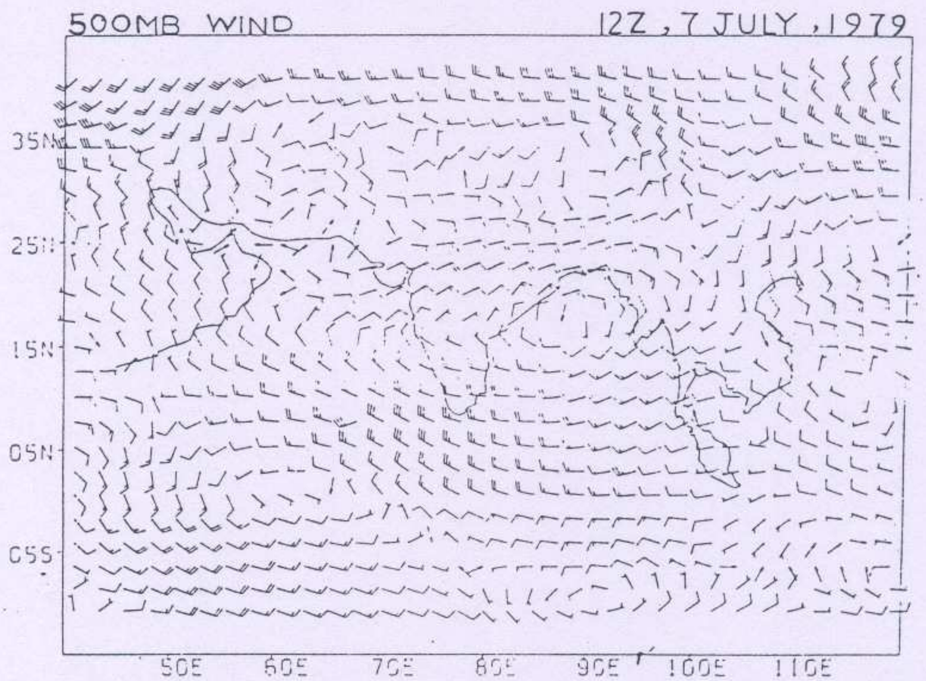


Fig. 2(b) : Same as Fig. 2(a) except at 500 mb.

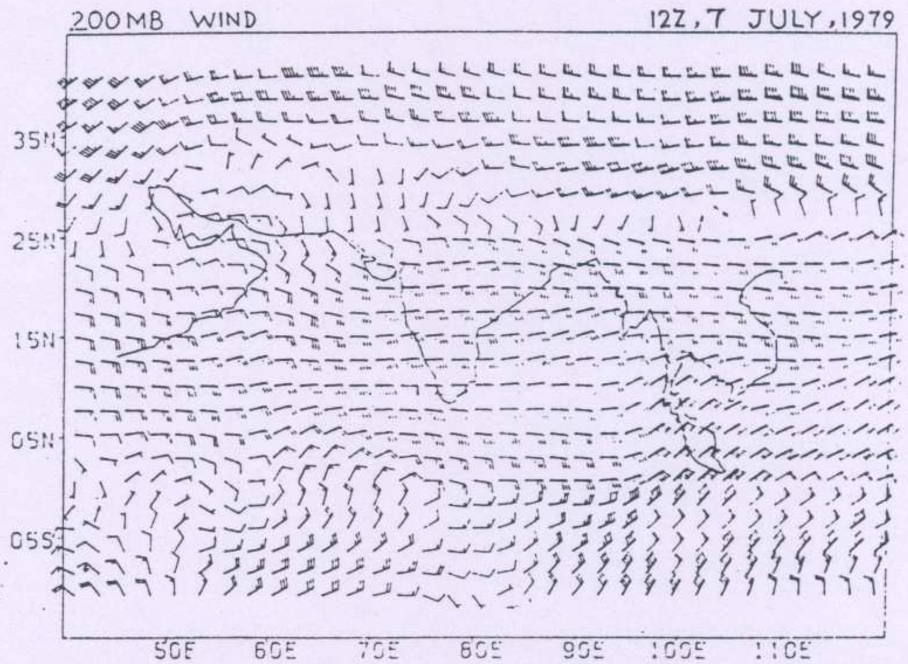
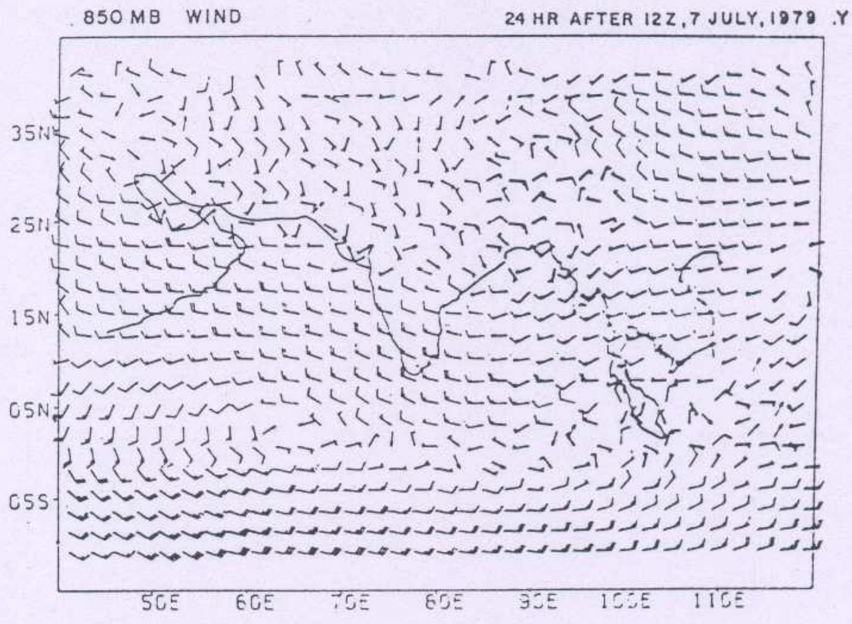


Fig. 2(c) : Same as Fig. 2(a) except at 200 mb.



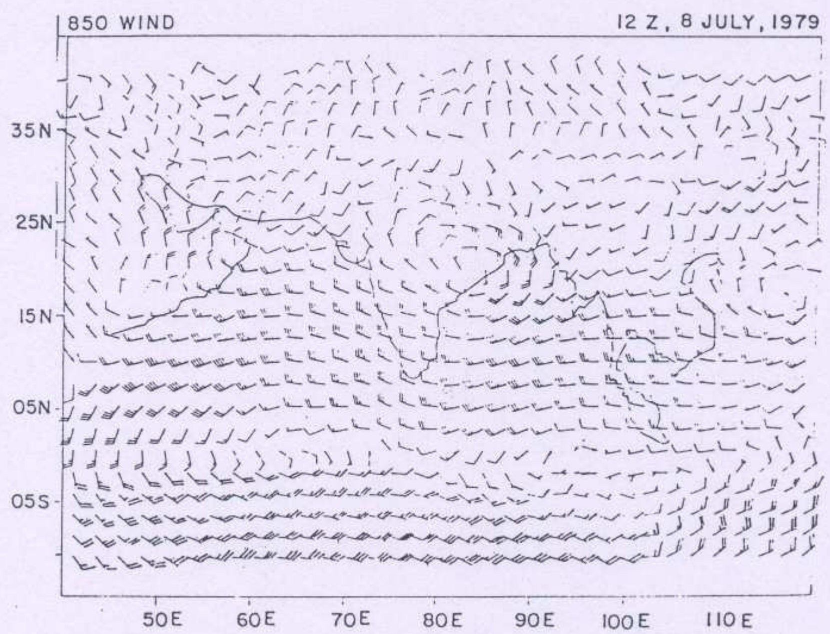


Fig.3(a) : The 24 hr forecast and corresponding verification wind charts at 850 mb.

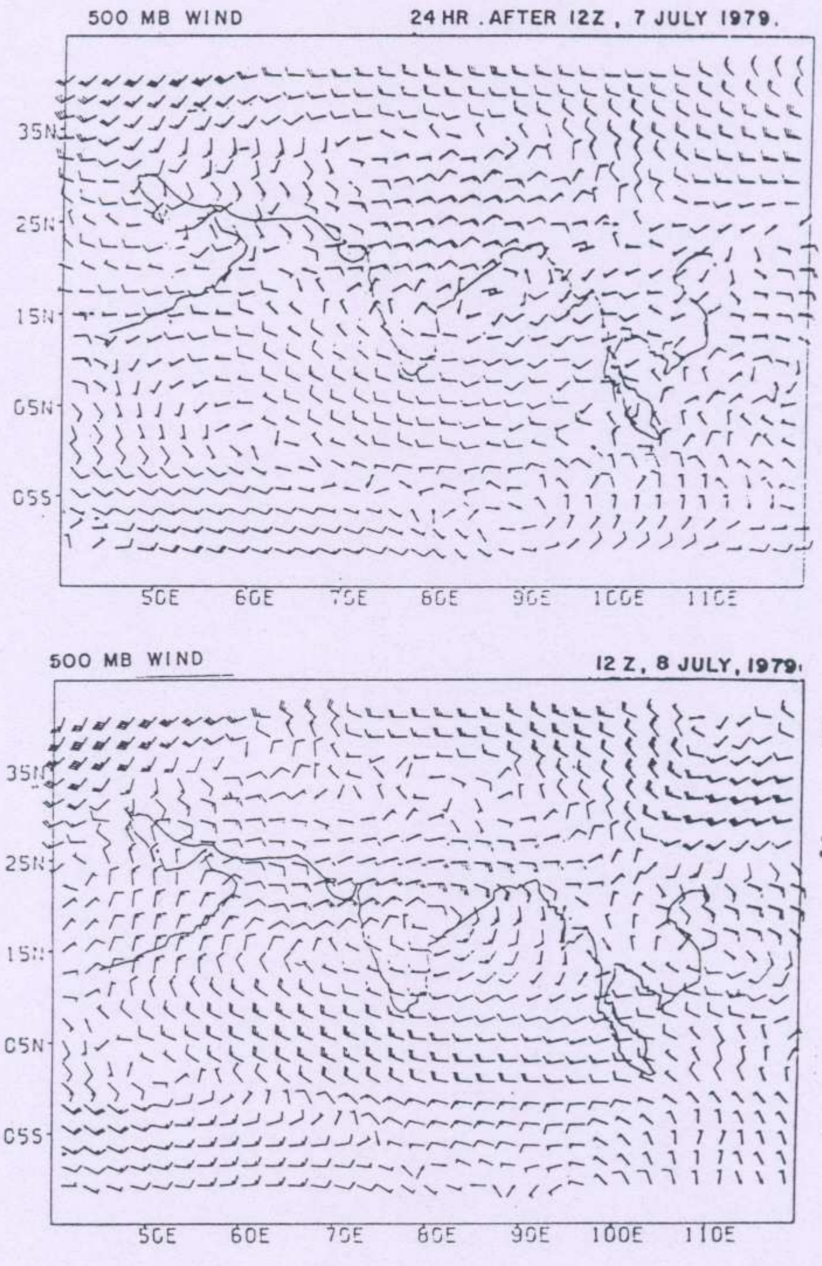


Fig. 3(b) : Same as Fig. 3(a) except at 500 mb level

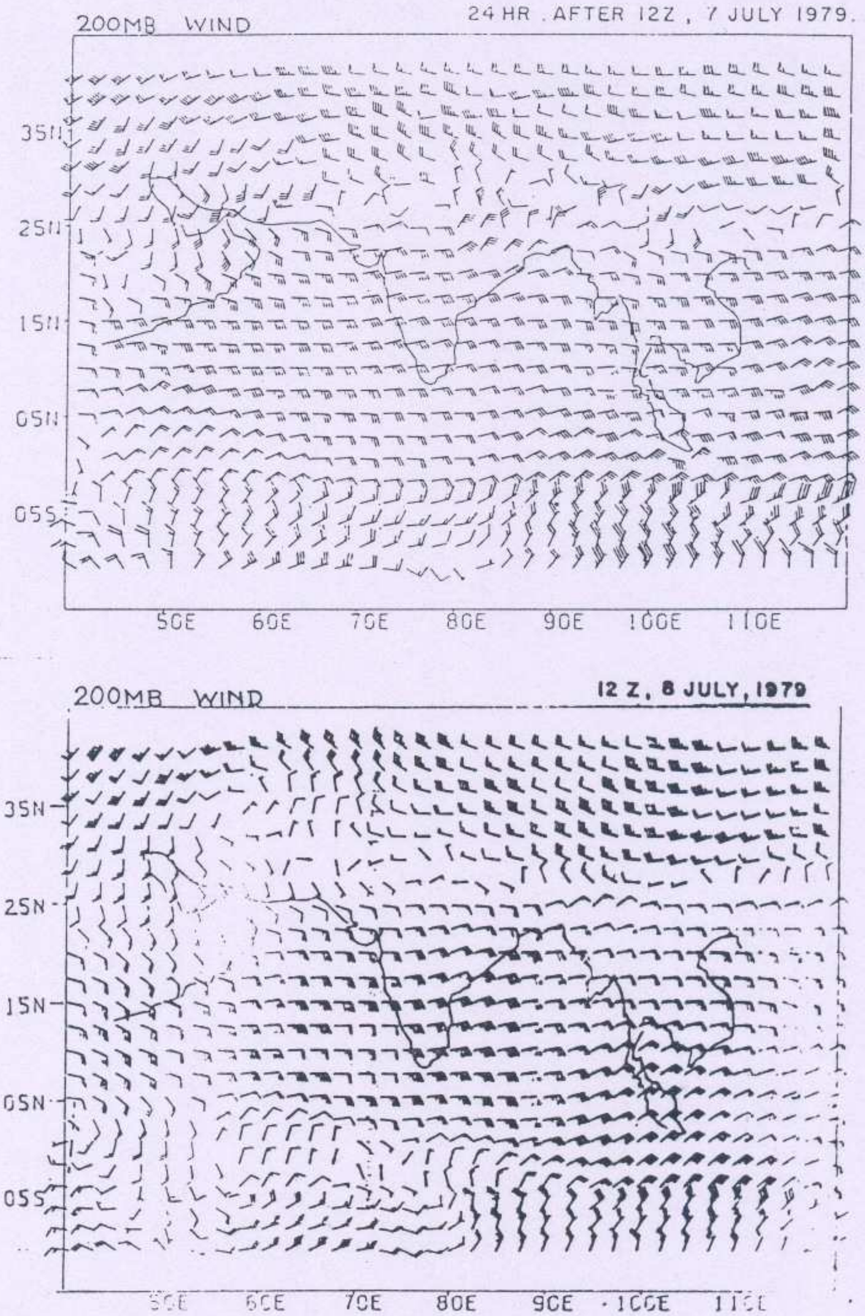


Fig. 3(c) : Same as Fig. 3(a) except at 200 mb level

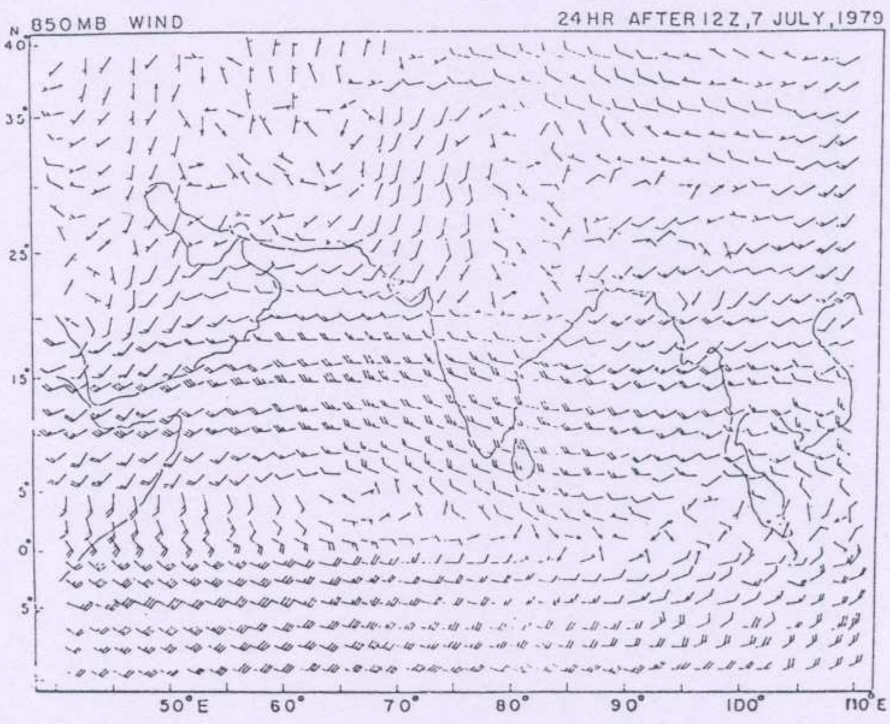


Fig. 4(a) : The 24 hr forecast wind charts at 850 mb level of extended domain

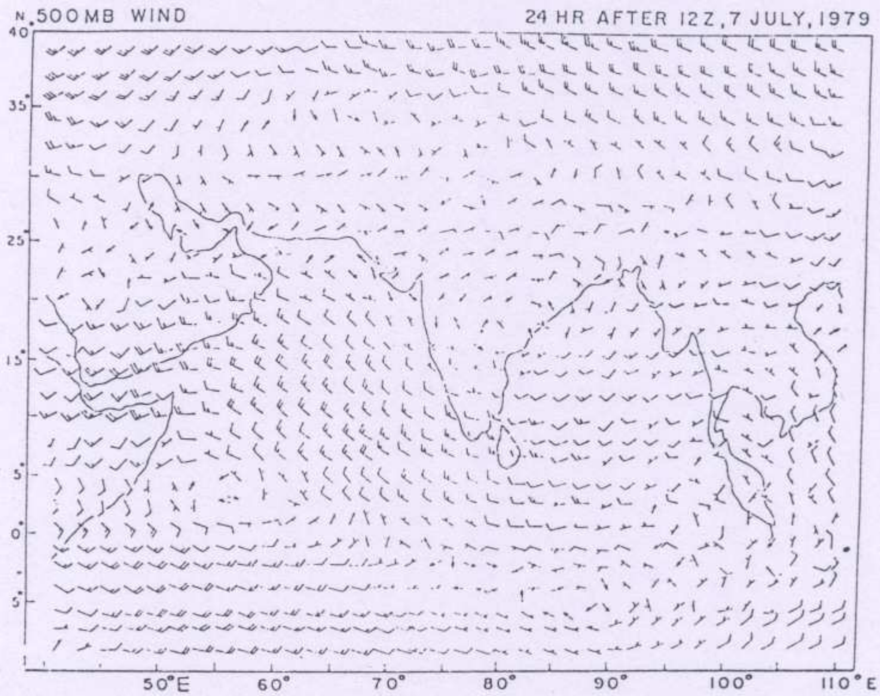


Fig. 4(b) : Same as Fig. 4(a) except at 500 mb level .

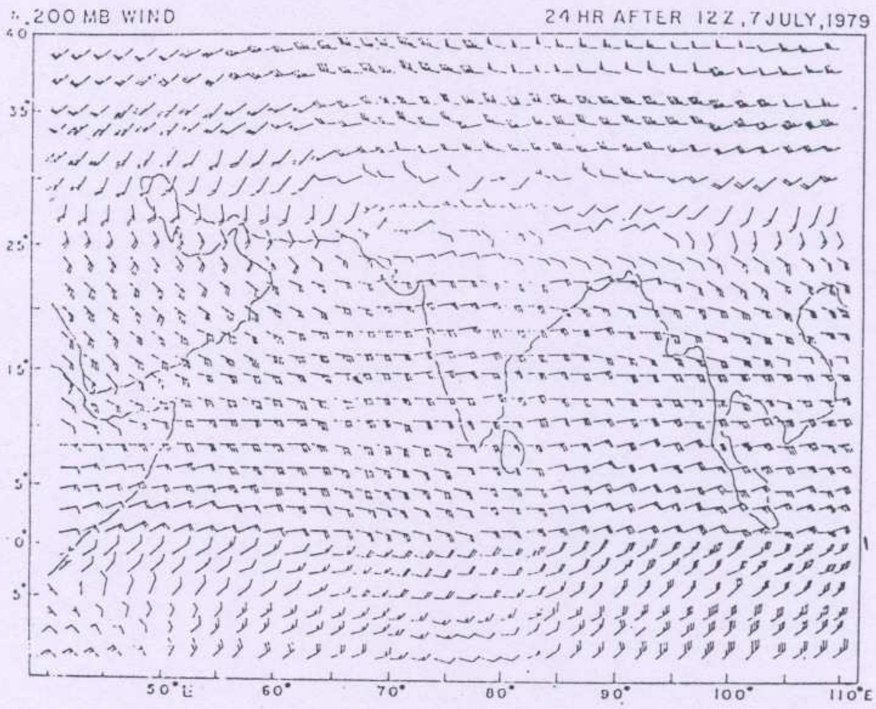


Fig. 4(c): Same as Fig.4(a) except at 200 mb level