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A DOCUMENTATION OF THE REGIONAL SIX LEVEL PRIMITIVE EQUATION MODEL

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OF THE REGIONAL SIX LEVEL PRIMITIVE EQUATION MODEL

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CONTENTS

1. Introduction

A sophisticated global model with high resolution in horizontal and in vertical is ideally suited for weather prediction and climate studies. However, the limited area (regional) models are obviously more economical than global (or hemispheric) models to produce 1-day, 2-day forecasts for a given horizontal resolution; or they can produce more accurate regional forecasts through the use of finer resolution only for the region of primary interest without tremendously increasing the computer time. In addition certain physical processes which are important for the particular geographical region such as effects of orography and cumulus convection can be more carefully modelled. Towards this objective, the development of regional models for monsoon prediction has been undertaken in the Indian Institute of Tropical Meteorology. The grid point approach has been adopted. A number of regional models have been developed and tested for monsoon prediction.

The regional model described in this document is a six level primitive equation model in sigma coordinate (Singh et al,1990a,1990b). The set of equations are in flux form. The fourth order accuracy finite difference scheme on Arakawa B-grid has been used for the computation of horizontal advection terms in momentum equation and other terms are calculated by second order accuracy schemes. A simple centred scheme with Asselin (1972) time filter has been used for marching in time. The physical processes included in the model are, large scale precipitation, cumulus convection, fluxes from the sea surface; surface friction and diffusion, PBL parameterization and dry convective adjustment. The model is integrated over Indian region extending from 15^{o} S to 40^{o} N and 40^{o} E to 120^{o} E with horizontal resolution of 200 km on Mercator projection. The model has been extensively used for monsoon prediction in research mode. The model has also been used for testing various parameterization schemes of cumulus convection, envelope orography, PBL parameterization and lateral boundary conditions.

In the following sections, the description of the model, the computational schemes and physical processes are discussed. The document further proceeds to describe the computer codes which consist of a main program and a number of subroutines for the forecast model.

2. Model Equations

The model equations are in sigma coordinate and are in flux form. The σ is defined as,

$$\sigma = \frac{p - p_T}{p_S - p_T} \qquad \ldots 1$$

The $p_S - p_T$ is denoted as π. The pressure p at any point on σ level is related with π as follows

$$p = \sigma \pi + p_T \qquad \ldots 2$$

The set of model equations are as follows :

Momentum Equations

$$\frac{\partial}{\partial t}\left(\frac{\pi}{m^2}u\right) = -\frac{\partial}{\partial x}(u^*u) - \frac{\partial}{\partial y}(v^*u) - \frac{\partial}{\partial \sigma}\left(\frac{\pi\dot{\sigma}}{m^2}u\right)$$
$$+\frac{\pi}{m^2}v\left\{f - v\frac{\partial m}{\partial x} + u\frac{\partial m}{\partial y}\right\} - \frac{\pi}{m}\frac{\partial \phi}{\partial x}$$
$$-C_p\frac{\pi\theta}{m}\frac{\partial P^{\kappa}}{\partial x} + \frac{\pi}{m^2}F_u - \frac{g}{m^2}\left(\frac{\partial \tau}{\partial \sigma}\right)_x \qquad \ldots 3$$

$$\frac{\partial}{\partial t}\left(\frac{\pi}{m^2}v\right) = -\frac{\partial}{\partial x}(u^*v) - \frac{\partial}{\partial y}(v^*v) - \frac{\partial}{\partial \sigma}\left(\frac{\pi}{m^2}\dot{\sigma}v\right)$$
$$-\frac{\pi}{m^2}u\left\{f - v\frac{\partial m}{\partial x} + u\frac{\partial m}{\partial y}\right\} - \frac{\pi}{m}\frac{\partial \phi}{\partial y}$$
$$-C_p\frac{\pi\theta}{m}\frac{\partial P^{\kappa}}{\partial y} + \frac{\pi}{m^2}F_v - \frac{g}{m^2}\left(\frac{\partial \tau}{\partial \sigma}\right)_y \qquad \ldots 4$$

Thermodynamic Energy Equation

$$\frac{\partial}{\partial t}\left(\frac{\pi}{m^2}\theta\right) = -\frac{\partial}{\partial x}(u^*\theta) - \frac{\partial}{\partial y}(v^*\theta) - \frac{\partial}{\partial \sigma}\left(\frac{\pi}{m^2}\dot{\sigma}\theta\right)$$
$$+\frac{\pi}{m^2}F_T + \frac{\pi}{m^2}D_T + \frac{g}{C_p}\frac{1}{m^2}\frac{1}{P^{\kappa}}\frac{\partial H}{\partial \sigma} \qquad \ldots 5$$

Equation for water vapour

$$\frac{\partial}{\partial t}\left(\frac{\pi}{m^2}q\right) = -\frac{\partial}{\partial x}(u^*q) - \frac{\partial}{\partial y}(v^*q) - \frac{\partial}{\partial \sigma}\left(\frac{\pi}{m^2}\dot{\sigma}q\right)$$
$$+\frac{\pi}{m^2}F_q + \frac{\pi}{m^2}M + \frac{g}{m^2}\frac{\partial E}{\partial \sigma} \qquad \ldots 6$$

Continuity Equation

$$\frac{\partial}{\partial t}\left(\frac{\pi}{m^2}\right) = -\frac{\partial u^*}{\partial x} - \frac{\partial v^*}{\partial y} - \frac{\partial}{\partial \sigma}\left(\frac{\pi\dot{\sigma}}{m^2}\right) \qquad \ldots 7$$

$\dot{\sigma}$ Equation

$$\left(\frac{\pi\dot{\sigma}}{m^2}\right)_{\sigma} = \left(\frac{\pi\dot{\sigma}}{m^2}\right)_{\sigma+\Delta\sigma} + \int_{\sigma}^{\sigma+\Delta\sigma} \left\{\frac{\partial}{\partial t}\left(\frac{\pi}{m^2}\right) + \frac{\partial u^*}{\partial x} + \frac{\partial v^*}{\partial y}\right\} d\sigma \qquad \ldots 8$$

Hydrostatic Equation

$$\frac{\partial \phi}{\partial \sigma} = -C_p\,\theta\,\frac{\partial P^{\kappa}}{\partial \sigma} \qquad \ldots 9$$

where

$$u^* = \frac{u\pi}{m}\ ,\ v^* = \frac{v\pi}{m}\ ,\ \kappa = \frac{R}{C_p}\ \ \text{and}\ \ P = \frac{p}{1000}$$

3. Vertical structure of the model

Fig. 1 shows the vertical structure of the model. The lower boundary level agrees with the earth's topography, where the surface pressure is defined. The upper boundary level is the 100 hPa pressure surface. The atmosphere between both the boundary levels is divided into six layers. The Computer code for computing σ values on model level are such that values of σ can be changed. In the present program sigma values are 17/18, 15/18, 12/18, 8/18, 4/18 and 1/18 corresponding to pressure values 950, 850, 700, 500, 300 and 150 hPa respectively. Broken line in Fig.1 shows the level where the values of horizontal velocity, potential temperature, water vapour and geopotential are specified. As no mass transport through the upper and lower boundary is assumed, the $\dot{\sigma} = 0$ at $\sigma = 0,1$ where $\dot{\sigma}$ is known as vertical σ velocity and is specified at the interfaces between the six layers of the model atmosphere.

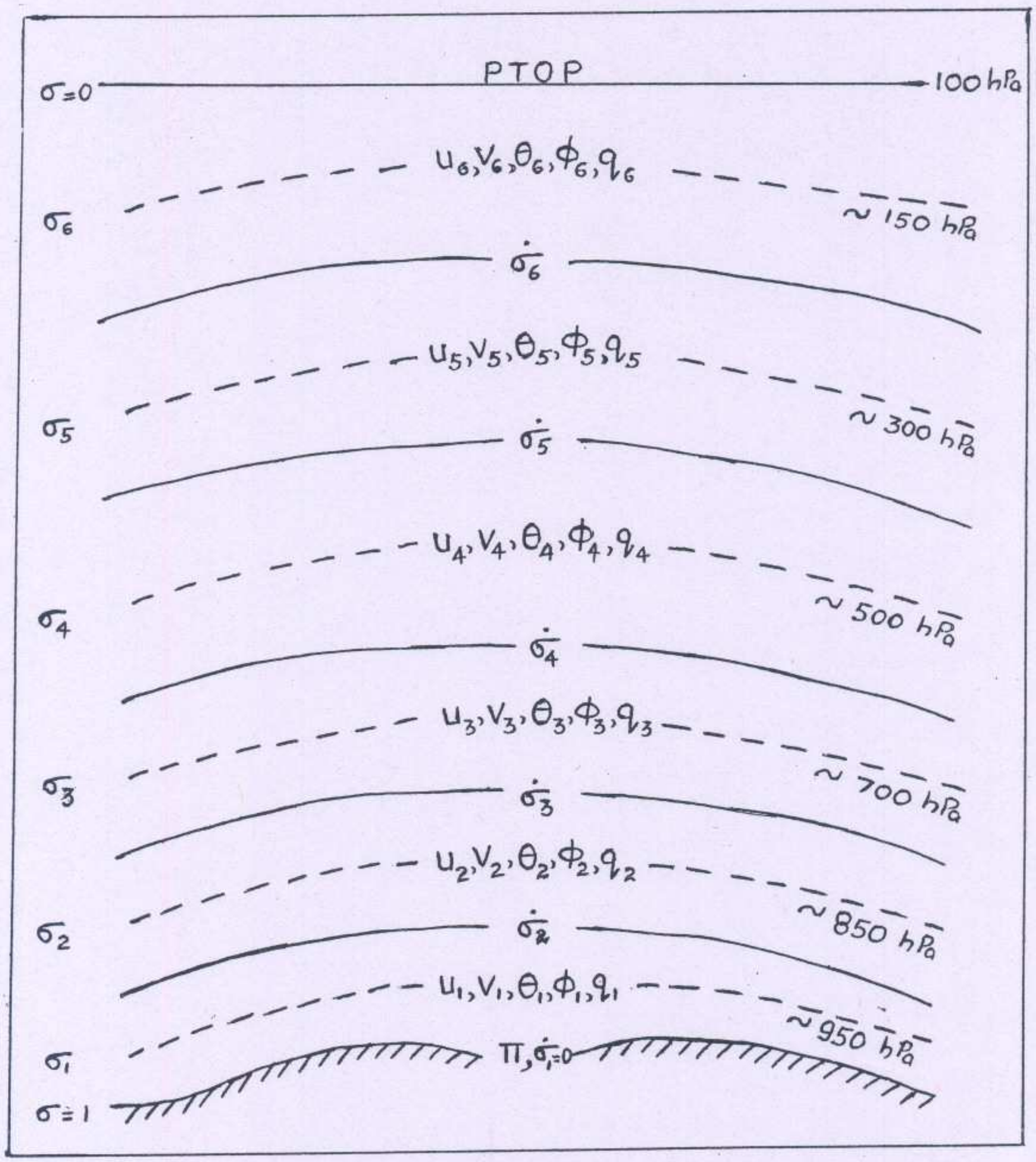

Fig. 1 : Vertical structure of the model

4. Horizontal domain and grid structure

The domain of integration extends from 15^{o}S to 40^{o} N and 45^{o} E 120^{o} E. The area is resolved into 41 x 29 grids of 200 km grid spacing on Mercator projection. A staggered grid is used in the horizontal as given in Fig. 2. Lateral boundary conditions are the time invariant fixed values.

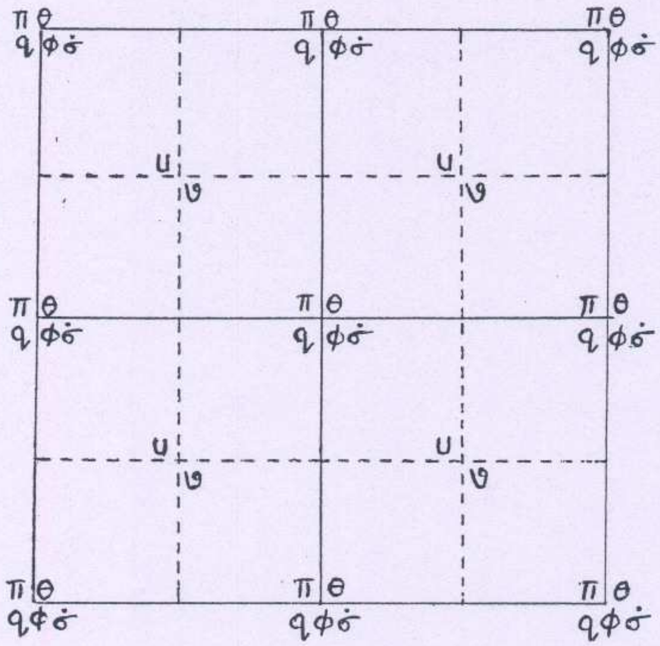

Fig. 2 Grid structure for finite differencing.

5. Finite difference scheme

Following Arakawa and Mintz (1974) and Arakawa and Lamb (1977) mass, energy, potential temperature and variance of potential temperature conserving finite difference scheme for space derivatives has been adopted. The horizontal advection terms in the momentum equations have been computed with fourth order accuracy difference scheme. Other terms in equations are computed with second order accuracy scheme. The finite difference scheme is briefly presented as follows :

5.1 Finite difference operators

The horizontal differencing in the x - direction for an arbitrary variable A may be written as (please see Fig. 3).

$$\delta_x A_0 = A_4 - A_8$$

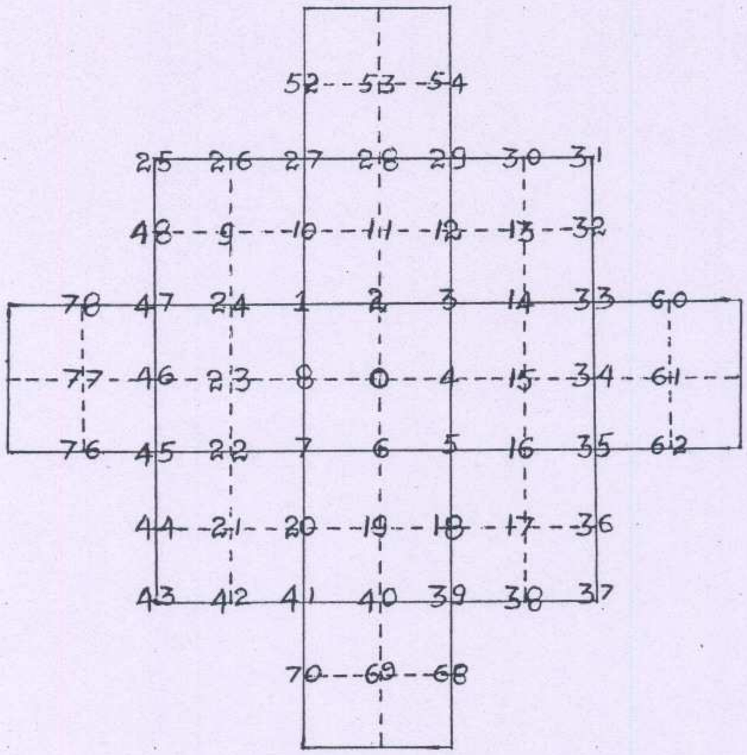

Fig. 3 : Index of the number of grid point used in the definition of finite difference operators.

and the averaging operator as

$$\overline{A_0}^{x} = (A_4 + A_8) / 2$$

Analogous expression can be made for the terms in the y- and σ-directions. The averaging over the surrounding four points may be expressed as

$$\overline{A_0} = (A_1 + A_3 + A_5 + A_7) / 4$$

using these notations, we may introduce the following finite difference operators. Concerning the horizontal momentum flux term, namely

$$\frac{\partial}{\partial x} (u^* u) + \frac{\partial}{\partial y} (v^* u)$$

we use the finite difference operator $D\left(\frac{u_0+u_l}{2}\right)$

such as

$$D\left(\frac{u_0+u_l}{2}\right) = 2 \times D_9\left(\frac{u_0+u_l}{2}\right) - D_{13}\left(\frac{u_0+u_l}{2}\right) \quad \ldots 10$$

where

$$\begin{aligned} D_9\left(\frac{u_0+u_l}{2}\right) = \frac{1}{12d} \Big\{ & (\overline{u_3^*}^x + \overline{u_5^*}^x)(u_0+u_{15}) \\ & - (\overline{u_1^*}^x + \overline{u_7^*}^x)(u_0+u_{13}) + (\overline{v_3^*}^y + \overline{v_1^*}^y)(u_0+u_{11}) \\ & - (\overline{v_5^*}^y + \overline{v_7^*}^y)(u_0+u_{19}) \Big\} \\ & + \frac{1}{24d} \Big\{ (\overline{u_3^*}^x + \overline{v_3^*}^y)(u_0+u_{13}) \\ & - (\overline{u_7^*}^x + \overline{v_7^*}^y)(u_0+u_{21}) - (\overline{u_1^*}^x - \overline{v_1^*}^y)(u_0+u_9) \\ & + (\overline{u_5^*}^x - \overline{v_5^*}^y)(u_0+u_{17}) \Big\} \end{aligned} \quad \ldots 11$$

$$\begin{aligned} D_{13}\left(\frac{u_0+u_l}{2}\right) = \frac{1}{24d} \Big\{ & (\overline{u_{11}^*}^y + \overline{u_{15}^*}^y + \overline{v_{11}^*}^x + \overline{v_{15}^*}^x)(u_0+u_{13}) \\ & - (\overline{u_{19}^*}^y + \overline{u_{23}^*}^y + \overline{v_{19}^*}^x + \overline{v_{23}^*}^x)(u_0+u_{21}) \\ & - (\overline{u_{11}^*}^y + \overline{u_{23}^*}^y - \overline{v_{11}^*}^x - \overline{v_{23}^*}^x)(u_0+u_{19}) \\ & + (\overline{u_{15}^*}^y + \overline{u_{19}^*}^y - \overline{v_{15}^*}^x - \overline{v_{19}^*}^x)(u_0+u_{17}) \Big\} \\ & + \frac{1}{24d} \Big\{ \overline{u_{15}^*}^y (u_0+u_{61}) - \overline{u_{23}^*}^y (u_0+u_{77}) \\ & + \overline{v_{11}^*}^y (u_0+u_{53}) - \overline{v_{19}^*}^y (u_0+u_{69}) \Big\} \end{aligned} \quad \ldots 12$$

$$u_2^* = \left(\frac{\overline{u}^y}{\overline{m}}\right)_2 \overline{\pi_2}^x \quad \ldots 13$$

$$v_4^* = \left(\frac{\overline{v}^x}{\overline{m}}\right)_4 \overline{\pi_4}^y \quad \ldots 14$$

d the grid distance and the subscript l the index for the surrounding grid points.

Following operator which guarantees total energy conservation is also defined,

$$D\left(\frac{u_0+u_l}{2}\right) = D_g\left(\frac{u_0+u_l}{2}\right) \qquad \ldots 15$$

Regarding the first term of the pressure gradient force i.e.

$$\frac{\pi}{m}\frac{\partial\phi}{\partial x}\ ,\ \frac{\pi}{m}\frac{\partial\phi}{\partial y}$$

we use the finite difference operator

$$G_x(\pi,\phi) = \frac{1}{2d}\,\frac{1}{\overline{m}_0}\left(\overline{\pi}_2^{\,x}\delta_x\phi_2 + \overline{\pi}_6^{\,x}\delta_x\phi_6\right) \qquad \ldots 16$$

$$G_y(\pi,\phi) = \frac{1}{2d}\,\frac{1}{\overline{m}_0}\left(\overline{\pi}_4^{\,y}\delta_y\phi_4 + \overline{\pi}_8^{\,y}\delta_y\phi_8\right) \qquad \ldots 17$$

and to the second term of the pressure gradient force, i.e.

$$\frac{\pi\theta}{m}\frac{\partial P^{\kappa}}{\partial x}\ ,\ \frac{\pi\theta}{m}\frac{\partial P^{\kappa}}{\partial y}$$

we adopt the finite difference operator

$$G_x(\pi\theta, P^{\kappa}) = \frac{1}{2d}\,\frac{1}{\overline{m}_0}\left(\overline{\pi}_2^{\,x}\overline{\theta}_2^{\,x}\delta_x P_2^{\kappa} + \overline{\pi}_6^{\,x}\overline{\theta}_6^{\,x}\delta_x P_6^{\kappa}\right) \qquad \ldots 18$$

$$G_y(\pi\theta, P^{\kappa}) = \frac{1}{2d}\,\frac{1}{\overline{m}_0}\left(\overline{\pi}_4^{\,y}\overline{\theta}_4^{\,y}\delta_y P_4^{\kappa} + \overline{\pi}_8^{\,y}\overline{\theta}_8^{\,y}\delta_y P_8^{\kappa}\right) \qquad \ldots 19$$

As to the horizontal flux term of potential temperature, i.e.

$$\frac{\partial}{\partial x}(u^*\theta) + \frac{\partial}{\partial y}(v^*\theta)$$

we utilise the finite difference operator

$$H\left(\frac{\theta_1+\theta_l}{2}\right) = \frac{1}{d}\left(u_2^*\overline{\theta}_2^{\,x} - u_{24}^*\overline{\theta}_{24}^{\,x} + v_{10}^*\overline{\theta}_{10}^{\,y} - v_8^*\overline{\theta}_8^{\,y}\right) \qquad \ldots 20$$

and this operator is also used for the horizontal advection of water vapour. In the special case, the above operators hold

$$H(1)_1 = \frac{1}{d}\left(u_2^* - u_{24}^* + v_{10}^* - v_8^*\right) \qquad \ldots 21$$

and this expression corresponds to the horizontal divergence

$$\frac{\partial u^*}{\partial x} + \frac{\partial v^*}{\partial y}$$

5.2 Finite difference equations

The original model differential equations (1) through (9) are approximated into finite difference equations. Hereafter, the subscripts 0 and 1 mean that the variable and the operator with these subscripts are evaluated at the grid point where the vector (for 0) and/or scalar (for 1) quantities are defined, respectively.

The finite difference form of the governing equations may be written for the adiabatic and frictionless case as follows :

$$\frac{\partial}{\partial t}\left(\left(\frac{\overline{\pi}}{m^2}\right)_0 u_0\right) = -D\left(\frac{u_a+u_\ell}{2}\right) - \frac{1}{\Delta\sigma}\,\delta_\sigma\left(\left(\frac{\overline{\pi\dot{\sigma}}}{m^2}\right)_0 \hat{u}_0\right) + \frac{\overline{\pi_0}}{\overline{m_0}^2}\, v_0 \left\{ \overline{f}_0 - v_0\frac{\partial m}{\partial x} + u_0\frac{\partial m}{\partial y}\right\} - G_x(\pi,\phi)_0 - C_p\, G_x(\pi\theta, P^\kappa)_0 \qquad \ldots 22$$

$$\frac{\partial}{\partial t}\left(\left(\frac{\overline{\pi}}{m^2}\right)_0 v_0\right) = -D\left(\frac{v_0+v_\ell}{2}\right) - \frac{1}{\Delta\sigma}\,\delta_\sigma\left(\left(\frac{\overline{\pi\dot{\sigma}}}{m^2}\right)_0 \hat{v}_0\right) - \frac{\overline{\pi_0}}{\overline{m_0^2}}\, u_0 \left\{ \overline{f}_0 - v_0\frac{\partial m}{\partial x} + u_0\frac{\partial m}{\partial y}\right\} - G_y(\pi,\phi)_0 - C_p\, G_y(\pi\theta, P^\kappa)_0 \qquad \ldots 23$$

$$\frac{\partial}{\partial t}\left(\frac{\pi_1\,\theta_1}{m_1^2}\right) = -H\left(\frac{\theta_1+\theta_\ell}{2}\right)_1 - \frac{1}{\Delta\sigma}\,\delta_\sigma\left(\frac{\pi_1}{m_1^2}\dot{\sigma}_1\,\hat{\theta}_1\right) \qquad \ldots 24$$

$$\frac{\partial}{\partial t}\left(\frac{\pi_1}{m_1^2}\, q_1\right) = -H\left(\frac{q_1+q_\ell}{2}\right)_1 - \frac{1}{\Delta\sigma}\,\delta_\sigma\left(\frac{\pi_1}{m_1^2}\dot{\sigma}_1\,\hat{q}_1\right) \qquad \ldots 25$$

$$\frac{\partial}{\partial t}\left(\frac{\pi_1}{m_1^2}\right) = -H(1)_1 - \frac{1}{\Delta\sigma}\,\delta_\sigma\left(\frac{\pi_1\,\dot{\sigma}_1}{m_1^2}\right) \qquad \ldots 26$$

$$\frac{\partial}{\partial t}\left(\frac{\pi_1}{m_1^2}\right) = -\sum_K H(1)_1 \qquad \ldots 27$$

$$\left(\frac{\pi_1 \dot{\sigma}_1}{m^2}\right)_{k-1} = \left(\frac{\pi_1}{m_1^2}\dot{\sigma}_1\right)_{k+1} + \Delta\sigma\left\{\frac{\partial}{\partial t}\left(\frac{\pi_1}{m_1^2}\right) + H(1)_1\right\}_k \qquad \ldots 28$$

$$\delta_\sigma(\phi_1)_{k+1} = -C_p\left\{\hat{\theta}_1\, \delta_\sigma(P_1^k)\right\}_k \qquad \ldots 29$$

$$\phi_1 = \frac{1}{\Delta\sigma}\delta_\sigma(\sigma\hat{\Phi}_1) + \sigma(\pi\mathcal{L})_1 \qquad \ldots 30$$

where $\Delta\sigma = \sigma_{k-1} - \sigma_{k+1}$ and the variable with the subscript $\wedge$ represents the value at the interface between the adjacent layer of the model atmosphere. For an arbitrary variable f, $\hat{f}$ is defined as

$$\hat{f}_k = (f_{k+1} + f_{k-1})/2 \qquad \ldots 31$$

As to the hydrostatic equation, we first integrate the finite difference equation (30) from surface to the first level of the model atmosphere. After the geopotential height of the first level is obtained we use only the equation (29) to deduce successively the geopotential height of the upper levels.

The finite differencing scheme described above guarantees that the motion in the model atmosphere conserves the following properties unless source/sink terms or boundary fluxes are present;

i) total mass of the model atmosphere is conserved

ii) total energy is conserved if the temporal change of the geopotential height at the top of the model atmosphere is ignored.

iii) potential temperature and its variance with respect to mass are conserved.

For the time intergration, Leap-frog scheme with Asselin time filter is used. The time step of 4 minutes is found suitable for 200 Km grid distance which satisfies CFL criteria.

6. Physical processes in the model

The following physical processes are incorporated in the model.

6.1 Horizontal diffusion

The expression for the diffusion terms F_u, F_v, F_θ and F_q is based on a fourth order Laplacian formulation with constant diffusion coefficients

$$F_u = -K_H \nabla \cdot \pi \nabla (\nabla_+^2 u) - K_{div}\, \pi \frac{\partial}{\partial x} \left(\nabla_+^2 (\nabla \cdot \vec{V}) \right) \qquad \ldots 32$$

$$F_v = -K_H \nabla \cdot \left\{ \pi \nabla (\nabla_+^2 v) \right\} - K_{div}\, \pi \frac{\partial}{\partial y} \left\{ \nabla_+^2 (\nabla \cdot \vec{V}) \right\} \qquad \ldots 33$$

$$F_\theta = -K_H \nabla \cdot \left\{ \pi \nabla (\nabla_+^2 \theta) \right\} \qquad \ldots 34$$

$$F_q = -K_H \nabla \cdot \left\{ \pi \nabla (\nabla_+^2 q) \right\} \qquad \ldots 35$$

where ∇_+^2 is a nondimensional Laplacian operator defined by

$$\nabla_+^2 X(x, y) = X(x+d, y) + X(x-d, y) + X(x, y+d) + X(x, y-d) - 4X(x, y) \qquad \ldots 36$$

The diffusion coefficients K_H and K_{div} used in the model are

$$K_H = K_{div} = 10^5 \ m^2 s^{-1}$$

where d is grid distance. These diffusion terms are evaluated on sigma plane.

The momentum equation includes two diffusion terms. The first term is the same as those in the thermodynamic and water vapour equations and it acts on both rotational and divergent components of u and v. When the momentum equation is converted to vorticity and divergence equations assuming π is constant, the diffusion terms become

$$\frac{\partial \zeta}{\partial t} = \cdots\cdots\cdots - K_H \nabla^2 (\nabla_+^2 \zeta) \qquad \ldots 37$$

$$\frac{\partial D}{\partial t} = \cdots\cdots\cdots - (K_H + K_{div}) \nabla^2 (\nabla_+^2 D) \qquad \ldots 38$$

where $\zeta \ (= K \cdot \nabla \times \vec{V})$ is vorticity and D $(= \nabla \cdot V)$ is divergence.

6.2 Vertical diffusion

The vertical eddy diffusion of momentum, heat and water vapour is evaluated by the following equations,

$$\begin{aligned} \vec{\tau} &= - \frac{\rho^2 g}{\pi} K_V \frac{\partial \vec{V}}{\partial \sigma} \\ H &= \frac{C_p \rho^2 g}{\pi} K_H \frac{\partial \theta}{\partial \sigma} \\ E &= \frac{\rho^2 g}{\pi} K_E \frac{\partial q}{\partial \sigma} \end{aligned} \qquad \ldots 39$$

where K_V, K_H and K_E are the vertical eddy viscosities for momentum, heat and water vapour respectively. They are defined by using mixing length model as follows :

$$K_V = K_H = K_E = l^2 \Psi$$

where l is mixing length and we assume l=30m.

The term Ψ is a function of wind shear and static stability defined as

$$\Psi = \sqrt{\frac{\rho g}{\pi} \left\{ \frac{\rho g}{\pi} \left(\frac{\partial V}{\partial \sigma} \right)^2 + \frac{g}{\theta} \cdot \frac{\partial \theta}{\partial \sigma} \right\}}$$

when $$l^2 \Phi \geq 1 \ m^2 sec^{-1}$$ and

$$l^2 \Phi = 1 \ m^2 sec^{-1}$$

when $$l^2 \Phi < 1 \ m^2 sec^{-1}$$ or inside the square root is negative. The vertical diffusion terms are applied to the lowest two levels of the model atmosphere.

6.3 Surface fluxes

The surface fluxes of momentum, heat and moisture are evaluated as follows

$$\tau_s = \rho_s C_D |V_s| V_s$$

$$H_s = \rho_s c_p C_H |V_s| (T_g - T_s), \ T_s = \theta_s \left(\frac{P_s}{P_0}\right)^{\kappa} \quad \ldots 4$$

$$E_s = \rho_s C_E |V_s| (q_g - q_s)$$

where C_D, C_H and C_E are bulk coefficients for momentum, heat and water vapour. Variables with the subscript ´s´ are defined at the level just above the earth´s surface ($\sim$ 10 m). $\mathbb{V}_s$, θ_s and q_s are defined by using the value of the lowest model level (about 50 hPa thickness above the surface) $\mathbb{V}_1$, θ_1 and q_1 as

$$\mathbb{V}_s = 0.8 \ \mathbb{V}_1 \quad \text{(over sea)}$$

$$= 0.69 \ \mathbb{V}_1 \quad \text{(over land)}$$

$$\theta_s = \theta_1$$

$$q_s = q_1$$

variables with subscript ´g´ are defined at the earth´s surface. Over sea T_g is estimated from the monthly normal sea surface temperature and q_s is assumed to be the saturation specific humidity at the estimated sea surface temperature.

The bulk coefficients over land are assumed as

$$C_D = 0.0043 \quad , \quad C_H = C_E = 0$$

i.e. surface flux of heat and water vapour is not evaluated over land in the model.

The bulk coefficients over sea are estimated as follows (the formulation is based on Kondo (1975))

$$C_D^* = (1.2 + 0.025\,|\mathbb{V}_S|) * 10^{-3}$$

$$C_H^* = 1.28 * 10^{-3}$$

where C_D^* and C_H^* are the temporal coefficient which are modified by a stability index S defined by

$$S = S_o \frac{|S_o|}{|S_o| + 0.01}$$

where

$$S_o = (T_g - T_s) / (\mathbb{V}_s^2 + 2.0)$$

Here

$$\frac{C_D}{C_D^*} = \frac{C_H}{C_H^*} = \frac{C_E}{C_E^*} = \begin{cases} 0.1 & S \leq -3.0 \\ 0.1 + 0.3S + 0.9e^{4.8S} & -3 < S < 0.0 \\ 1.0 + 0.47\sqrt{S} & 0.0 \leq S \leq 3.0 \end{cases}$$

6.4 Cumulus parameterization

The cumulus parameterization scheme used in the present model are following Kuo (1965, 1974). Kuo (1965) considered that the cumulus convection always occurs in region of deep layers of conditionally unstable stratification over areas of mean low level convergence and that the vertical profiles of temperature and humidity inside the cloud follow those of a moist adiabat. The drawback of this scheme was that it underestimated tropical rainfall rates and it was also found that in this scheme there is disproportionate partitioning of the large scale moisture supply. Kuo (1974) suggested remedy for this by introducing moistening parameter ´b´. Thus bI, where I is large scale moisture supply, goes for moistening of cloud column and (1-b) I goes for heating. He also suggested that b should be very much less than one in regions of low level convergence in tropics. In the present model, cumulus parameterization based on Kuo (1974) type cumulus convection following Kanamitsu et al (1983) is adopted. The details of the scheme adopted in the present model are as follows :

6.4.1 The conditions for invoking convection

The convection is invoked if following three conditions are satisfied.

i) The convection is assumed to take place if layer is conditionally unstable. The conditionally unstable layer is the layer in which

$$\frac{\partial \theta_e}{\partial p} > 0$$

where θ_e is the equivalent potential temperature defined as

$$\theta_e = \theta e^{L q_s / C_p T}$$

where q_s is the saturated specific humidity at environmental temperature T and pressure p. The cloud base is assumed to be the first level above the lowest sigma level which is conditionally unstable. The cloud top is defined as the level where cloud temperature becomes equal to the environmental temperature.

ii) The second condition to be satisfied is that the large scale moisture convergence in the grid box be positive. The large scale convergence of moisture is defined as

$$I = \int_{\sigma_B}^{\sigma_T} \frac{\partial q}{\partial t} d\sigma$$

Subscript B and T are for bottom and top of the cloud.

iii) The third condition for invoking convection is that the mean relative humidity of the environment in the cloud column is greater than 0.81 i.e.

$$\langle RH \rangle = \frac{\int_{\sigma_B}^{\sigma_T} q \, d\sigma}{\int_{\sigma_B}^{\sigma_T} q_s \, d\sigma} > 0.81$$

6.4.2 Cumulus parameterization scheme

The large scale moisture convergence I is partitioned into two parts.

$$I = I_\theta + I_q$$

where I_θ is the part of the moisture supply which goes into enhancing the temperature field and I_q is the part that modifies the moisture field. I_θ and I_q can be expressed in terms of I as

$$I_\theta = (1 - b) I$$

and

$$I_q = b I$$

where b is the moistening parameter introduced by Kuo (1974) and is the fraction of available moisture supply that modifies the moisture field.

The amount of moisture needed to cover the entire grid volume by a model cloud defined by T_c and $q_c(T_c)$ of the local moist adiabat is given by

$$Q = Q_\theta + Q_q$$

where Q_θ is the amount of moisture necessary to raise the large scale temperature to cloud temperature and is given by

$$Q_\theta = -\frac{C_p}{L}\int_{\sigma_B}^{\sigma_T} (T_c - T)\, d\sigma$$

and Q_q denotes the supply of moisture required to change the environmental humidity from q to a local moist adiabatic q_s.

It is expressed as

$$Q_q = -\int_{\sigma_B}^{\sigma_T} (q_s - q)\, d\sigma$$

Two additional parameters a_θ and a_q are also introduced and are defined as

$$a_\theta = \frac{I_\theta}{Q_\theta}$$

$$a_q = \frac{I_q}{Q_q}$$

They are constants of proportionality for heating and moistening by clouds.

The heating and moistening rates at each level are expressed as follows :

$$\frac{\partial T}{\partial t} = a_\theta\, (T_c - T)$$

$$\frac{\partial q}{\partial t} = a_q\, (q_s - q)$$

In the present model the moistening parameter b is assumed zero, it means, only heating is allowed when convection is invoked.

6.5 Large scale condensation and stable heating

Large scale condensational heating is simulated in the present model by removal of supersaturation (RH > 1) whenever it is encountered in the model prediction. Supersaturation in the model could be generated by the vertical advection of moisture in regions of large scale ascent of air having absolutely stable (with respect to moist adiabat) lapse rates and by other processes such as radiational cooling etc.

If the relative humidity exceeds 100% the excess water vapour condensed out instantaneously the new temperature and mixing ratio is computed by iterative method. The new temperature T´ and new mixing ratio q_s computed as follows,

$$q_s(T') = q_0 - \frac{q_0 - q_s(T)}{1 + \frac{L}{C_p}\frac{0.622}{p}\frac{e_s\, 7.5\, l_n 10 * 237}{(t_c + 237)^2}}$$

$$T' = T + \frac{L}{C_p}\left(q_0 - q_s(T')\right)$$

where t_c is old temperature in $^{\circ}$C, p is the pressure at that level in hPa, other symbols have their usual meanings. Two to three iterations are found sufficient for convergence. Condensed moisture is assumed to fall down to ground as precipitation without evaporation.

6.6 Dry convective adjustment

Over the desert areas, due to strong solar heating there is possibility of attaining super adiabatic lapse rates ($-\frac{\partial T}{\partial \sigma} > \gamma_d$) in the atmosphere. This type of stratification may lead to overturning on the grid scale. This type of instability is removed by dry convective adjustment. Whenever superadiabatic lapse rates are encountered, by performing dry convective adjustment the superadiabatic lapse rate is brought back to dry adiabatic lapse rate conserving the integral of the dry static energy ($C_pT + gZ$) over the layer involved. The net effect of this adjustment is to cool the lower part of the model atmosphere and warm the upper part. In a crude way this is a parameterization of the heat transfer accomplished in the real atmosphere by dry convective overturning.

The adjustment scheme can be outlined as follows :

The dry convective adjustment is carried out for the layer if $-\frac{\partial\theta}{\partial P} < 0$. Let P_B and P_T be the pressure values for bottom and top of the layer. Let Z_B and T_B be geopotential height and temperature corresponding to P_B . Then dry static energy of that layer is

$$E_B = gZ_B + C_p T_B$$

The dry static energy along the adjusted sounding can be expressed as

$$E_{adj} = gz + C_p T$$
$$= \text{Constant}$$

since dry static energy is to be conserved

$$\int_{P_T}^{P_B} (gz + C_pT)\,dP = \int_{P_T}^{P_B} E_{adj}\,dP$$
$$= E_{adj}\,(P_B - P_T)$$

or

$$E_{adj} = \frac{1}{P_B - P_T}\int_{P_T}^{P_B} (gz + C_pT)\,dP$$

Since Z_B does not change after the adjustment T_B can be obtained as

$$(T_B)_{adj} = \frac{1}{C_p}\,(E_{adj} - gZ_B)$$

Since the potential temperature is constant along the adjusted sounding, temperature of other levels can be computed as

$$T = \left(\frac{P}{P_B} \right)^{K} (T_B)_{adj}$$

In practice the dry static stability is checked again after the dry adjustment and if new super adiabatic lapse rates have occurred, the above procedure is repeated until dry instability is eliminated over the entire column of air.

7. Description of the model code

7.1 Grid structure

As mentioned before, in the horizontal, Arakawa-B type of grid is used. In this arrangment zonal and meridional wind components are defined at the centre of grid lattice. In the east-west direction number of grid points are IM. I=1 is western boundary point and I=IM is the eastern boundary point. In the north-south direction there are JM grid points. J=1 is the northern boundary point and J=JM is the southern boundary point. As wind components are defined at the centre of grid lattice,the number of grid points in east-west direction are IM-1 and in north-south direction are JM-1.The levels in the vertical are labelled from bottom ,the lowest level being K=1.

7.2 Parameter Definitions

Parameter	Definition
IM	Number of grid points

	in E-W direction
JM	Number of grid points in N-S direction
KM	Number of model levels
KMPBL	Number of model levels within PBL

7.3 Common Block Description

i) Block name KUO

These block variables are used in subroutines KUO74, TETENS and DRYCNV. The block contains following variable names.

Variable name	Description of the variables
IJMAX	Total number of grid points in horizontal domain (IM * JM)
KMAXM	KM-1
TWDELT	Time step used for marching in time
CL	Latent heat of vaporization. 25.1208×10^5 Joules Kg^{-1}
CP	Specific heat of air at constant pressure 1004.6 Joules $Kg^{-1} {}^oK^{-1}$
GRAV	Acceleration due to gravity
GASR	Specific gas constant 287.04 Joules $Kg^{-1} {}^oK^{-1}$
AKAPPA	R/Cp (= 0.286)
PTOP	Pressure at the top of the model atmosphere

KONS	Integer constants defined in main program
CONS	Real constants used to define critical value of relative humidity and temperature
SIGKAP	$\sigma^{R/CP}$ values for various σ levels
SIGKIV	$(1/\sigma^{R/CP})$ values for various levels
SIGKUO	σ_k values
DELSGK	Same as $\Delta\sigma_k$
SINCLT	$1/m$ at scalar points (1D)
NORAD	This is index for including simulated radiation, NORAD=1 then radiation is included.
IWVADJ	Index for mixing water vapour in unstable case in routine DRYCNV

ii) **Block name TABLE**

These common block variables are computed in subroutine FTABLE and are used in routines KU074, TETENS, PKCALC

Variable name	Description of the variables
PKAPA	$(P/1000)^{R/C_p}$ for p values from 1 to 1000 hPa with increment of 1.
FLOG	log of x, x varies from 1 to 1000 with increment of 1.
TETENS	Saturated vapour pressure values in hPa for temperatures $-150^{o}C$ to $99.9^{o}C$ at the interval of $0.1^{o}C$.

7.4 Equivalence Statement

The variable QQ (IM, JM, 4*KM+1) is used to store variables U,V, PT, WV and PAI at the present time step.

The variable QQP (IM, JM, 4*KM+1) is used to store U, V, PT, WV and PAI values for the previous time step.

QQMT (IM, JM, 4* KM+1) is used to store tendency values of U, V, PT, WV and PAI.

7.5 Main Program : MODEL

This is the main program in which input data is read, forcing terms are computed, variables are extrapolated in time, effect of physical processes is computed and added to the prognostic variables at every time step and forecast is obtained for desired time in hour. Flow diagram for forecast model is shown in fig 4.

Routines called : CNSTS
BAR
FTABLE
SUBTRC
OMEGA
SETBD
PKCALC
HEIGHT
CLEAR
MOVE
PAIMCL
TENDCY
TENDCV
EXTRP

Start

Read values of latitude(FLAT), longitude(FLONG), coriolis parameter(F) and map factor(XM) from the disk file.

Read input parameters:

$\{$Tsea, Qsea, π, u, v, θ, ϕ, q, rainfall(=0) at KT=0$\}$

ISTEP=0 KT=0

CLEAR

Equate flux form tendency-terms to zero

$$\left\{\frac{\partial}{\partial t}\frac{\pi}{m^2},\ \frac{\partial}{\partial t}\frac{\pi}{m^2}u,\ \frac{\partial}{\partial t}\frac{\pi}{m^2}v,\ \frac{\partial}{\partial t}\frac{\pi}{m^2}\theta,\ \frac{\partial}{\partial t}\frac{\pi}{m^2}q\right\}$$

PAIMCL

Compute $(\pi/m^2)^{n-1}$

TENDCY

Compute forcing terms in prognostic equations and hence flux form tendencies :

$$\left\{\frac{\partial}{\partial t}\frac{\pi}{m^2},\ \frac{\partial}{\partial t}\frac{\pi}{m^2}u,\ \frac{\partial}{\partial t}\frac{\pi}{m^2}v,\ \frac{\partial}{\partial t}\frac{\pi}{m^2}\theta,\ \frac{\partial}{\partial t}\frac{\pi}{m^2}q\right\}^n$$

FIG.4

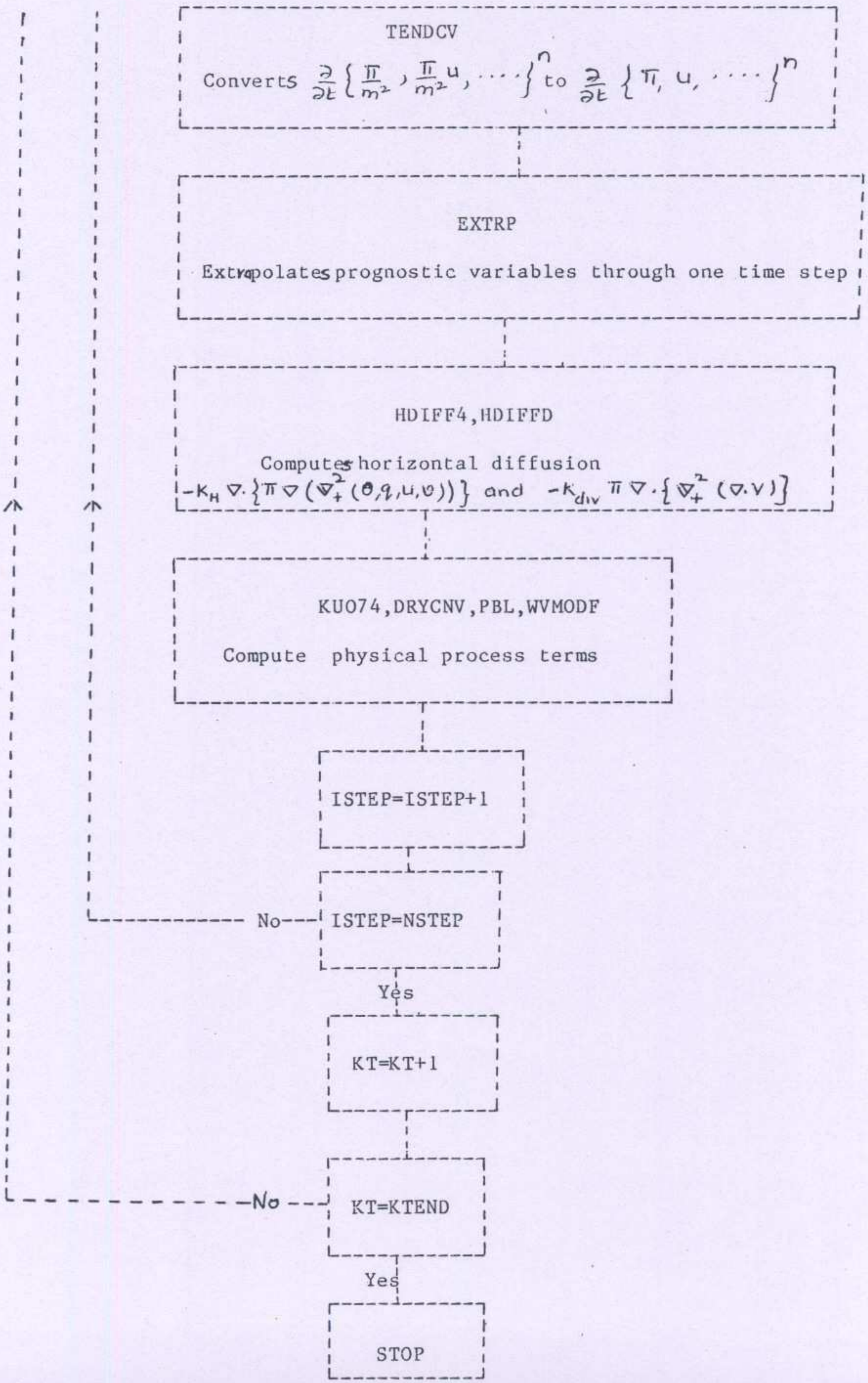

Fig. 4 : Flow diagram for the forecast model

HDIFF4

HDIFFD

WVMODF

KU074

DRYCNV

PBL

WVCAST

Description :

A-B This section defines the parameters related to the time of integration, the grid distance (DELS), pressure at the top (PTOP) of the model atmosphere and time filter values used for time integration.

B-C Values of (SIG) can be changed by changing the values of SIGG given in DATA statement.

LOOP 80 computes $\Delta\sigma_k$ values (=DELSIG), σ values at dotted levels (=SIG) and at the solid levels (=SIGML). This section reads latitude, longitude values, coriolis parameter and map factor of the grid

points from record on the disk file.
LOOP 555 converts coriolis parameter (W1) and map factor (SM) into two dimensional variables.
LOOP 777 initialises the rainfall rates (RRR, RRL, RRC) to zero
LOOP 110 converts two dimensional 1/m values into one dimensional 1/m values (=SINCLT).

C-D This section defines variables required for KU074 subroutine IKUO=1 means KUO convection is included, NORAD=1 means simulated radiation is included.

D-E In this section three routines are called. The routines CNSTS and BAR computes variables related to map factor and coriolis parameter. The third routine FTABLE tabulates the values of T/θ (=PKAPA) for a range of pressure values 1 to 1100 hPa and saturated vapour pressure values for temperature range - 150°C to 99.9°C at the interval of 0.1°C

E-F This section reads the input data. The input data consists of two records on the disk file. The first record includes the parameters IDATE: year, date, month and time in GMT, PS surface pressure in hPa, ZPFM geopotential height in meters on standard pressure levels, TSEA sea surface temperature in ^{o}C, QSEA saturated mixing ratio at TSEA in $gmKg^{-1}$, PHIS orographic height in m^2s^{-2}. The second record consists of IDATE, KT time in hours, PAI ($=Ps-P_{top}$) values in hPa, U zonal wind components in ms^{-1}, V meridional wind component in ms^{-1}, PT potential temperature in ^{o}K, WV mixing ratio in $gmKg^{-1}$, RRR total rainfall in mm/day and DPHI geopotential height in m^2s^{-2} on σ surfaces.

If (KTSTAR) is zero it computes vertical velocity, besides reading initial input data.

LOOP 75 modifies rainfall (RRR) values to avoid double counting in leap frog scheme. After every 24 hours of integration rainfall values are reset to zero.

F-G This section does the prediction of

all prognostic variables. The flux form tendencies QQMT (UMT,VMT,PTMT,WVMT and PAIMT) are computed.

$\frac{\partial}{\partial t}\left(\pi x / m^2\right)$ where x can be u, v, θ, q and π

From these, simple tendency terms $\frac{\partial x}{\partial t}$, are computed and the variables are extrapolated through one time step.

G-H The subroutines related to the physical processes are called and the variables are updated.

H-I In this section ISTEP is incremented by 1 and if ISTEP is an exact multiple of NSTEP, KT is incremented by 1, otherwise sections F-G and G-H are repeated. If KT is an exact multiple of KTOUT new values of ω and ϕ are computed. The forecast results are written on disk file at this time. If KT is less than KTEND the prediction procedure is repeated.

7.6 Subroutines

This section describes the computer code of the subroutines. The description includes, name of the routine, its purpose, from which routine it is called list of routines called in the routine and expla nation of computer codes.

Routine Name : TENDCY

It computes tendencies (in flux form) of all prognostic variables.

Called from : MODEL

Routines called : UVSTA

PAITS

TADV

WVADV

BAR

UVHADV

UVVADV

BAR

CORIOL

PKCALC

HEIGHT

PGFORC

Description :

A-B — Computes the values of $u\pi/m$ (=USTA), $v\pi/m$ (VSTA), $\dot{\sigma}\pi/m^2$ and $\frac{\partial}{\partial t}\frac{\pi}{m^2}$ (PAIMT)

B-C — This section computes horizontal and vertical advection terms in the thermodynamic energy equation and the moisture continuity equation. Thus the tendency terms for potential temperature and mixing ratio in flux form are obtained.

C-D This section computes horizontal advection, vertical advection, coriolis force and pressure gradient terms in u and v momentum equations and tendencies for u and v in flux form are obtained.

Routine Name **UVSTA**

It computes $u\pi/m$ (=USTA) and $v\pi/m$ (=VSTA) values.

Called from : TENDCY

Routines called : CLEAR

Description :

A-B Subroutine CLEAR initialises the USTA and VSTA values to zero.
LOOP 5 computes $\overline{\pi}^{x}$ (=W),
LOOP 10 computes USTA values.
LOOP 15 computes $\overline{\pi}^{y}$ (=W) and
LOOP 20 computes VSTA.

Routine Name : **PAITS**

This routine computes π tendencies and $\dot{\sigma}\frac{\pi}{m^2}$ values.

Called from : TENDCY

Routines called : NONE

Description :

A-B LOOP 100 computes horizontal divergence (=D) for all the levels in vertical and
LOOP 200 computes $\frac{\partial}{\partial t}\pi/m^2$

B-C LOOP 300 and 320 computes $\pi\dot{\sigma}/m^2$ values at levels 2 to KM. LOOP 350 equates $\dot{\sigma}\pi/m^2$ values at σ level to zero, which is the prescribed boundary condition.

Routine Name : **TADV**

This routine computes flux form tendency values for potential temperature $\frac{\partial}{\partial t}(\pi\theta/m^2)$

Called from : TENDCY

Routines called : None

Description :

A-B DS (= $1/2\Delta S$) and RSIG ($=1/2\Delta\sigma$) are computed.

B-C LOOP 100 computes horizontal advection terms in thermodynamic energy equation and adds to PTMT

C-D LOOP 200 computes vertical advection terms in thermodynamic energy equation and adds to PTMT. And thus complete flux form tendency $\frac{\partial}{\partial t}\left(\frac{\theta\pi}{m^2}\right)$ is obtained (excluding effect of physical processes).

Routine Name : **WVADV**

It computes horizontal and vertical advection terms in moisture continuity equation

Called from : TENDCY

Routines called : None

Description :

A-B IM1, JM1 and KM1 are defined. DS=1/2*DELS and RSIG ($=1/2\Delta\sigma$) terms are computed.

B-C This section computes all the horizontal advection terms for all vertical levels.

C-D LOOP 200 computes vertical advection terms for K=1 and K=KWVM.

D-E LOOP 300 computes vertical advection terms for K=2,KM1. This completes the computations of $\frac{\partial}{\partial t}\left(\frac{q\pi}{m^2}\right)$

Routine Name : **UVHADV**

This routine computes horizontal advection terms in u and v momentum equations by 13 points Jacobian scheme suggested by Arakawa and Mintz (1974). This scheme has 4th order accuracy.

Called from : TENDCY

Routines called : None

Description :

A-B IM1, JM1, IM2, JM2, IM3, JM3
DS(= - 1/12 DELS), DS2=DS3(=-1/24DELS)
are defined.

B-C LOOP 1000 is the main LOOP for vertical levels LOOP 110, 120, 130, 140, 150, 210, 220, 230 deals with the 9 points Jacobian scheme for horizontal advection terms in u momentum equation. LOOP 160,170, 180, 250, 260 are connected with 9 point Jacobian scheme for horizontal advection term in v momentum equation.

C-D Evaluates the horizontal advection terms in u and v momentum equations by 13 points Jacobian scheme. This completes the computation of horizontal advection terms in u and v momentum equations.

Routine Name : **UVVADV**

Vertical advection term in u or v momentum equations is computed

Called from : TENDCY

Routines called : None

Description :

A-B Defines IM2, JM2 and computes 1/ $2\Delta\sigma$(=RSIG) values

B-C The vertical advection term in momentum equation is computed.

Routine Name : CORIOL

This routine computes the coriolis force and map factor terms in u and v momentum equations.

Called from : TENDCY

Routines called : None

Description :

A-B LOOP 1000 computes coriolis force terms and map factor terms in u and v momentum equations and these are added into UMT and VMT

Routine Name : **PGFORC**

It computes pressure gradient terms in u and v momentum equations

Called from : TENDCY

Routines called : None

Description :

A-B This section defines IM1, JM1, IM2, JM2

CP, CP2 (= CP/2) values and computes 1/4*DELS (RDELS4) values.

B-C Computes pressure gradient terms of u momentum equation.LOOP 210 computes π values at u* points, LOOP 200 is for levels. LOOP 220 computes both the pressure gradient terms(=W2).
LOOP 230 adds them into UMT.

C-D Computes pressure gradient terms of v momentum equation. LOOP 310 computes values at v* (=W1) points.
LOOP 300,320, 330 computes pressure gradient force and adds it to VMT.

This completes the computations of U, V, PT, WV and PAI tendencies (excluding the effect of physical processes).

Routine Name : **TENDCV**

This routine converts flux form tendency of all the five prognostic variables into simple tendency terms i.e., $\frac{\partial}{\partial t}\frac{x\pi}{m^2} \rightarrow \frac{\partial x}{\partial t}$ where x can be u,v,θ,q and π

Called from : MODEL

Routines called : None

Description :

A-B This section defines the variables KVE, KPTS, KWVE, KPAI. It also defines IM1, JM1, IM2 and JM2.

B-C LOOP 100 predicts the values of Π/m^2 for next time step amd stores in W1.

LOOP 110 computes predicted Π/m^2 values at vector points and stores in W2. It also computes Π tendency values at vector points (W3).

LOOP 120 and 130 computes 1/W1 and 1/W2 values respectively. LOOP 200 computes $\partial u / \partial t$ and $\partial v / \partial t$

LOOP 300 computes $\partial \theta / \partial t$ and $\partial q / \partial t$. LOOP 400 computes $\partial \Pi / \partial t$ terms.

Routine Name : **EXTRP**

It extrapolates one prognostic variable in time by using leap frog scheme with Asselin time filter, each time it is called.

Called from : Main program

Routines called : None

Description :

A-B IMAX, JMAX and C (= DUMP/2) are defined. C is the time filter constant.

B-C LOOP 10 extrapolates value

of the prognostic variables at $t+\Delta t$ and also time filtering is done.

LOOP 20 is for time extrapolation of q and time filtering is not applied for this variable.

Routine name : **PKCALC**

It is used to compute T/θ values

Called from : MODEL,TENDCY

Routines called : None

Description :

A-B	LOOP 10 computes pressure values on σ levels and then T/θ values are interpolated for these pressure values from T/θ values already tabulated in FTABLE.

Routine Name : **HEIGHT**

It computes geopotential height values from the temperature values using hydrostatic relation.

Called from : MODEL, TENDCY

Routines called : None

Description :

A-B	LOOP 10 computes pressure values at σ levels.

B-C LOOP 70 and 80 computes values of geopotential height by hydrostatic relation.
LOOP 100 computes DPHI at the first call.

Routine name : **FTABLE**

It tabulates values of saturated vapour pressure values for temperature range -150^oC to 99.9^oC and T/θ values for range of pressure values (P) 1-1100 hPa and log p values.

Called from : MODEL

Routines called : None

Description :

A-B It defines R/C_p (AK) and (1/1000) ($=p_o$) values.
LOOP 10 tabulates $(p/p_o)^{R/C_p}$ (=PKAPA) and log x =1,1100 values.

B-C LOOP 20 tabulates values of saturated vapour pressure values

Routine name : **CNSTS**

Computes different constants related to the map factor and coriolis parameter.

Called from : MODEL

Description :

A-B LOOP 4 computes coriolis parameter

at vector points (FB)

LOOP 12 computes m^2 (=SM2) and $1/m^2$

(RSM2) at scalar points(m is map factor)

LOOP 22 computes 1/m (RSMB) and

$1/m^2$ (RSMB2) at vector points.

LOOP 24 computes $\partial m/\partial x$ (DMX)

$\partial m/\partial y$ (DMY) at vector points.

Routine Name : **OMEGA**

It computes vertical p velocity at σ levels

Called from : MODEL

Routines called : None

Description :

A-B This section computes $\frac{\partial(\pi/m^2)}{\partial t}$

LOOP 5 computes $\frac{\Delta\sigma}{4\Delta x}$(DSIGD4) and

$\sigma/4\Delta x$ (=SIGD4) values.

LOOP 20 computes u/m values at

u* points (=US)

LOOP 25 computes v/m values at v*

points (=VS).

LOOP 10 is the main loop for computations of $\partial/\partial t(\pi/m^2)$ term.

LOOP 30 computes $u\pi/m$ and LOOP 35

computes $v\pi/m$ values at u* and v*

points respectively.

LOOP 40 and 50 computes divergence and adds it layer by layer from top of model to bottom, this is $\frac{\partial}{\partial t}(\pi/m^2)$ (=OMG)

B-C LOOP 60 equates A to $\frac{\partial}{\partial t}(\pi/m^2)$ and sets $\dot{\sigma}$ to zero at $\sigma=1$.

LOOP 100 computes $\pi\dot{\sigma}/m^2$ at middle of the layers.

LOOP 210 computes $\pi\dot{\sigma}/m^2$ at the middle of the top most layer of model atmosphere.

LOOP 300 computes vertical p-velocity at σ levels.

Routine name : **CLEAR**

It equates the variable array to zero.

Called from : MODEL,UVSTA, PBL

Routines called : None

Description :

A-B LOOP 10 equates the variable array to zero.

Routine name : **MOVE**

It equates one variable array to other variable array

Called from : MODEL

Routines called : None

Description :

A-B LOOP 10 equates variable array B to variable array A.

Routine name : **SUBTRC**

It substracts second variable from first variable in argument list and stores it in first variable array.

Called from : MODEL

Routines called : None

Description :

A-B LOOP 10 substracts second variable array B from the first variable array A and it is stored in array A.

Routine name : **BAR**

It computes arithmatic mean of the values. It is mainly used to compute mean of scalar point variables to get a vector point value and vice versa.

Called from : MODEL, PBL

Routines called : None

Description :

A-B LOOP 10 computes mean of four points of array A and stores it in array B.

Routine name : **PAIMCL**

It computes π / m^2 values.

Called from : MODEL

Routines called : None

Description :

A-B LOOP 10 computes π/m^2 values and stores them in PAIM variable array.

Routine name : **WVMODF**

This routine equates mixing ratio values to zero if it is less than 1×10^{-10} gm/Kg

Called from : MODEL

Routines called : None

Description :

A-B LOOP 10 equates WV values to zero if it is less than 1×10^{-10} gm/Kg

Routine name : **RPKCAL**

It computes θ/T values for given pressure p.

Called from : PBLPT

Routines called : None

Description :

A-B LOOP 5 computes $(p/1000)^{-R/Cp}$ values for range of p=1 to 1000.

B-C LOOP 100 interpolates values of $(p/1000)^{-R/Cp}$ or θ/T values for a given pressure ´p´ using values computed in section A-B.

Routine name : **SETBD**

It equates the values of the parameter at boundary points to that of the boundary-1 grid points.

Called from : MODEL

Routines called : None

Description :

A-B	LOOP 10 equates the boundary values at north and south boundaries to that at one grid point interior for all the grid points in the east-west direction(JMAX-1).
	LOOP 20 equates the boundary values at east and west boundaries to that at one grid point interior for all grid points in north-south direction IMAX-1.

Routine name : **MOVE1**

Equates one dimensional variable array A to another variable B.

Called from : HDIFFD

Routines called : None

Description :

A-B	LOOP 10 equates variables in array A to array B.

Routine name : **WVCAST**

To set the predicted mixing ratio value just below its saturation value if WV is supersaturated.

Called from : MODEL

Routines called : None

Description :

A-B	LOOP 100 is for levels. LOOP 10 computes temperature T and pressure (P) values using π and σ values. LOOP 20 computes mixing ratio (W) at T, P with relative humidity value as 0.999 LOOP 30 sets the value of WV equal to W if WV > W.

Routine name : **HDIFF4**

This routine computes linear horizontal diffusion terms with fourth order Laplacian for u, v, θ and q.

Called from : MODEL

Routines called : None

Description :

A-B	It defines constants related to number of levels in vertical, grid points in horizontal and $1/\Delta s$ values.
B-C	It defines coefficient for diffusion CDIF.

LOOP 20 computes π / m^2 (W) at scalar points.

LOOP 25 computes $\Delta t*(\pi / m^2)$ at scalar points.

LOOP 30 computes $\Delta t(\pi / m^2)$ at vector points (RPAIMB).

C-D In this section horizontal diffusion terms for θ and q are computed. It is further added into predicted values of θ and q.

D-E It computes horizontal diffusion terms in the momentum equations and are added to the predicted values of u and v.

Routine name : **HDIFFD**

It computes divergent part of the horizontal diffusion for u and v.

Called from : MODEL

Routines called : None

Description :

A-B It defines diffusion coefficient for divergent part of horizontal diffusion. This section computes horizontal divergence and Laplacian of divergence.

B-C The divergent part of horizontal

diffusion for u and v are computed and added to the predicted u and v values.

Routine name : **PBL**

It computes the exchange of momentum, heat and moisture between surface and atmosphere.

Called from : MODEL

Routines called : CLEAR

PBLUV

PKCALC

PBLPT

BAR

PBLWV

Description :

A-B This defines constants such as gas constant R, G (= g,accelaration due to gravity), JM1, IM1, JM2, IM2.

B-C It tabulates values of C_D/C_D^* (=RCDT) and C_H/C_H^* (=RCHT) for stability index S for the range -30 to +30.

C-D This generates land/sea indices SL (for scalar points), SL1 (for vector points), 1 over sea and

0 over land.

D-E The density values and related terms are computed.

LOOP 30 computes density at intermediate levels from gas law equation for levels 2 to KPBL

LOOP 32 computes density at the surface (= ROA (I,J,1)).

LOOP 34 computes the terms $\rho^2 g/\pi\Delta\sigma$ (=ROB) and $\rho g/\pi\Delta\sigma$ (=ROA) for levels 2 to KPBL .

E-F This section computes wind components at the surface and temperature at 10 metre height.

F-G This section computes exchange coefficients for momentum, heat and moisture.

G-H This section computes vertical diffusion coefficients K_v ($=K_\theta = K_q$) and then $\rho^2 g/\pi\Delta\sigma * K_v$ (= CK)

H-I The stress terms τ_s and τ are computed. Calls PBLUV twice to add the PBL stress effects to u and v.

I-J The turbulent exchange of heat and moisture H_{σ},H and E_{σ},E are computed. Calls PBLPT and PBLWV to add the effects of turbulent exchange of heat and moisture to θ and q respectively.

Routine name : **PBLUV**

It computes frictional effect term $\left(\frac{\partial \tau}{\partial \sigma}\right)_x$ and $\left(\frac{\partial \tau}{\partial \sigma}\right)_y$ in u and v momentum equations.

Called from : PBL

Routines called : None

Description :

A-B It computes $(g/m^2)\left(\frac{\partial \tau}{\partial \sigma}\right)\Delta t$ terms and adds it to predicted values of u or v.

Routine name : **PBLPT**

This routine computes vertical eddy flux of sensible heat

Called from : PBL

Routines called : None

Description :

A-B It computes the term for vertical transport of sensible heat in thermodynamic energy equation $\frac{g}{m^2}\frac{1}{(P_0/P)^{R/C_p}}\frac{\partial H}{\partial \sigma}\Delta t$ and adds it to the values of predicted potential temperature.

Routine name : **PBLWV**

It computes the vertical eddy flux of moisture.

Called from : PBL

Routines called : None

Description :

A-B It computes the term $\frac{g}{m^2} \frac{\partial E}{\partial \sigma}$ in the moisture equation and adds it to the predicted values of q.

Routine name : **KUO74**

It computes heating and moistening effects and rainfall due to deep convection following KUO (1974). It also simulates radiation effects.

Called from : MODEL

Routines called : TETENS

Description :

A-B The constants, which are used in this routine are defined.

LOOP 5 computes T(K+1)/T(K) along dry adiabat.

LOOP 600 computes TLAREA and is used for computing areal average of rainfall.

LOOP 3000 converts predicted value of q (=GWV) and previous time step value of q (=GWVM) into gm/gm.

B-C The main LOOP for heating and

moistening by deep convection starts here. LOOP 10 is for J and LOOP 100 for I.

LOOP 6 computes saturated q values, corresponding to temperatures GTMP for all levels and initialises variables CONDC, CONDL, QTRN to zero.

C-D Below the level KCLMIN (=2) the large scale heating is computed, q is adjusted accordingly.

D-E TMOIST and QMOIST are T and q along the moist adiabat at K+1 level.

E-F The moist stability and supersaturation are checked. Stability and supersaturation leads to large scale heating. This section computes large scale heating under above mentioned conditions.

F-G In case, moist instability is present and if there is increase in moisture at LCL, T and q along moist adiabat upto cloud top (=KCLT) are computed. Otherwise check the possibility of cloud development from next level.

G-H LOOP 2130 computes the moisture convergence in the cloud layer. If it is negative convection is not invoked.

If it is positive, LOOP 2140 computes mean relative humidity in cloud column. If mean RH exceeds critical value defined by CONS(2) (=81%) the moistening parameter ´b´ is set zero and convection is invoked. Otherwise procedure is repeated for the next level.

H-I The a_e and heating due to deep convection are computed. No moistening takes place as b=0.

LOOP 2210 removes the excess moisture due to supersaturation. This is end of convective heating.

If KCLT+1 < KMAX (=KM) the sections from D-E to H-I are repeated. If K=KMAX then stable heating is computed.

LOOP 620 computes large scale, convective and total rainfall.

I-J Radiational cooling is computed in this section. Areal average of the heating due to condensation is computed (DTEMP) and is substracted from the temperature.

LOOP 3001 converts GWV and GWVM into gm/kg.

Routine : **TETENS**

It computes saturated q for given pressure and temperature.

Called from : KU074

Routines called : None

Description :

A-B	Defines constants which are used in this routine.
B-C	Computes saturated vapour pressure values (TETEN)
C-D	Computes saturated q value (SATQ) and DSATQ which is equal to

$$\frac{L}{C_p} * \frac{0.622}{P} \; \frac{e_s * 7.5 \ln 10 * 237}{(t_c + 237)^2}$$

8. **Model produced forecast**

The model was tested for a few synoptic cases of June,July and August 1979. We present the results of 12 GMT 7 July 1979, a case of intense monsoon depression. The data is extracted from the FGGE IIIb global grid point data of ECMWF. The model is integrated upto 48 hrs.

The initial flow field is shown in Figure 5. The forecast and corresponding verification wind charts are shown in Figure 6. Track of the monsoon depression is shown in Figure 7. Predicted and observed rainfall rates are shown in Figure 8. For this experiment, the grid distance of 200 km, time step of 4 minutes and six levels in vertical corresponding to 950,850,700,500,300 and 150 hPa are used.

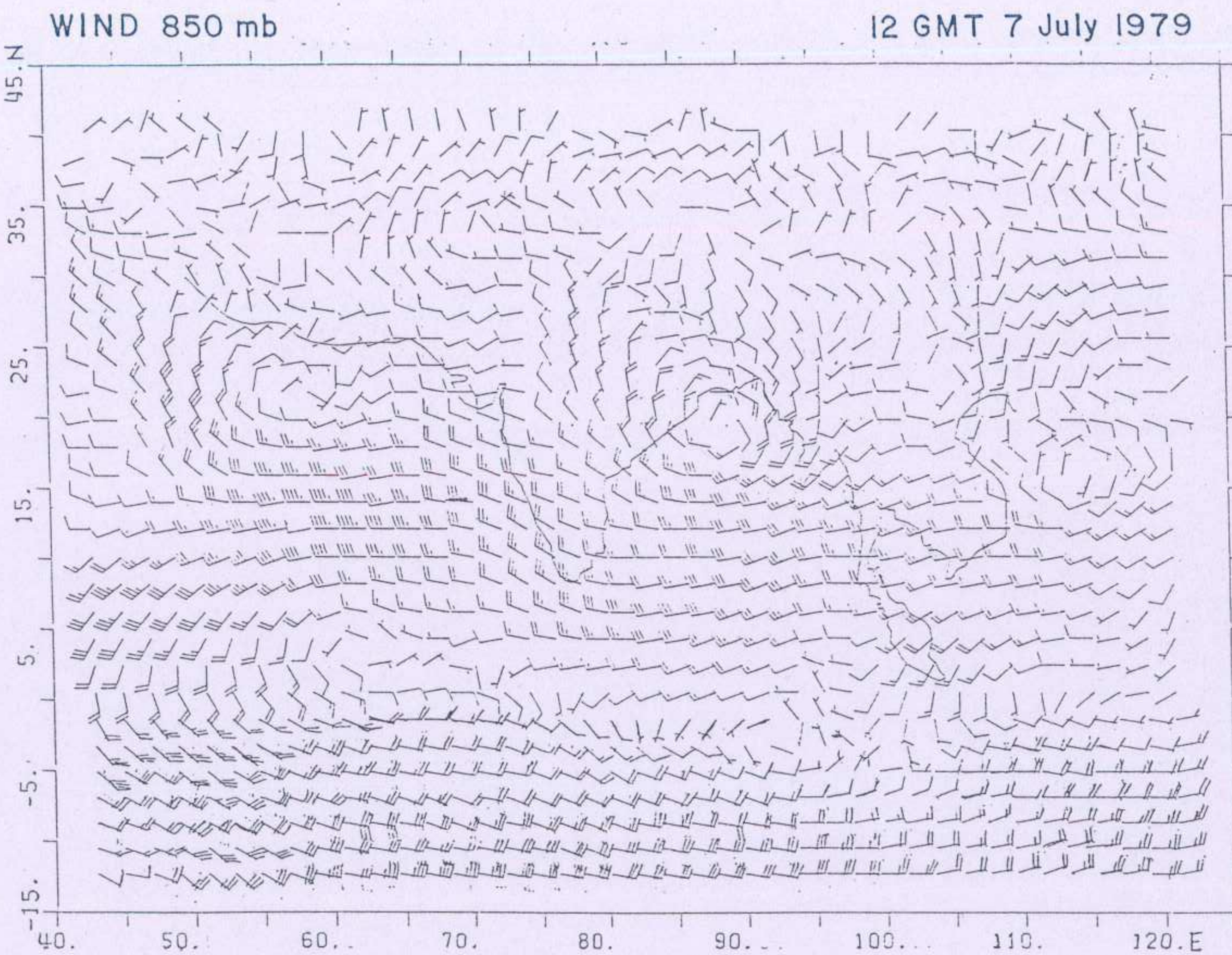

Fig. 5 : 850 hPa wind field on 12 GMT 7 July 1979

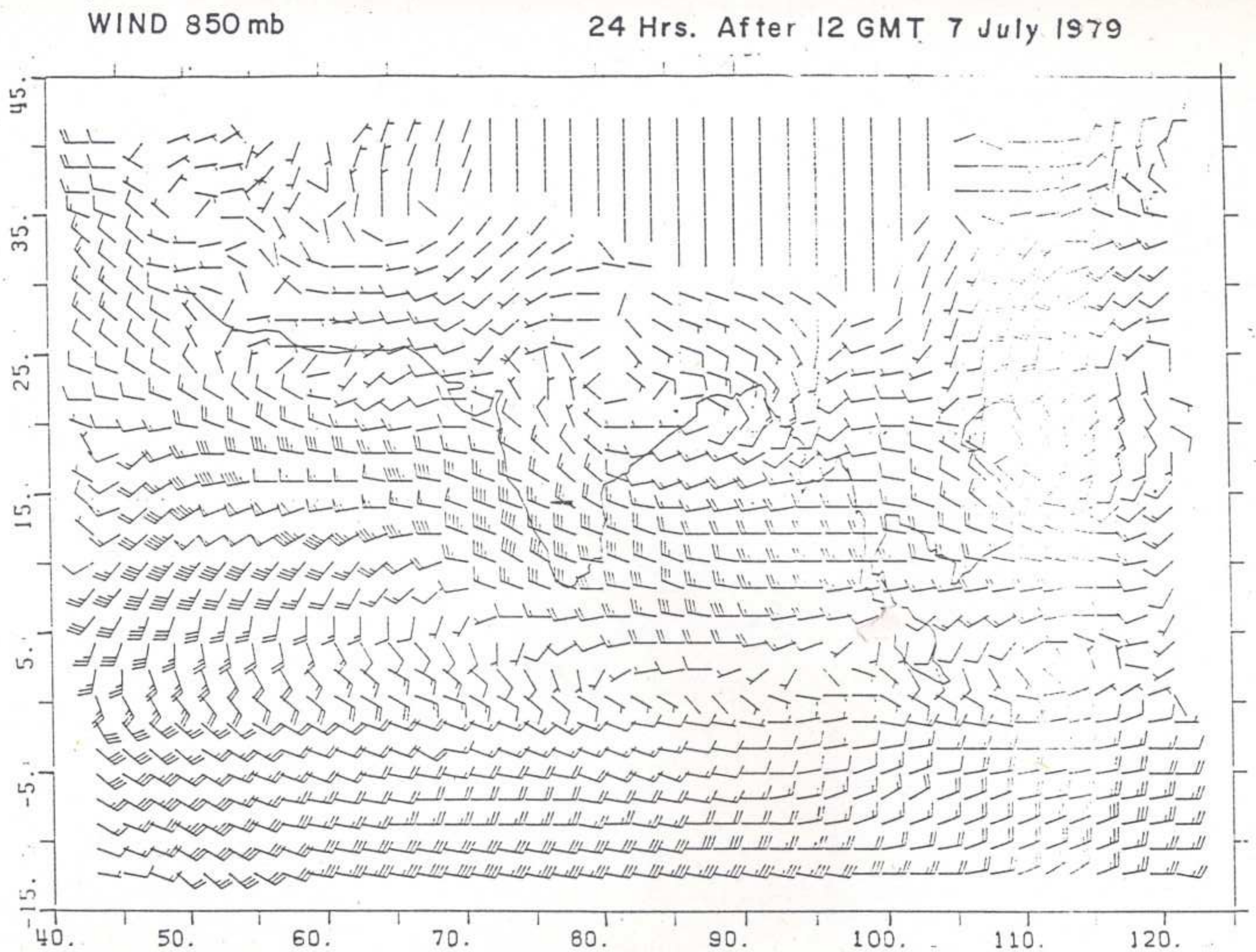

Fig. 6a : 24 hr predicted wind field at 850 hPa

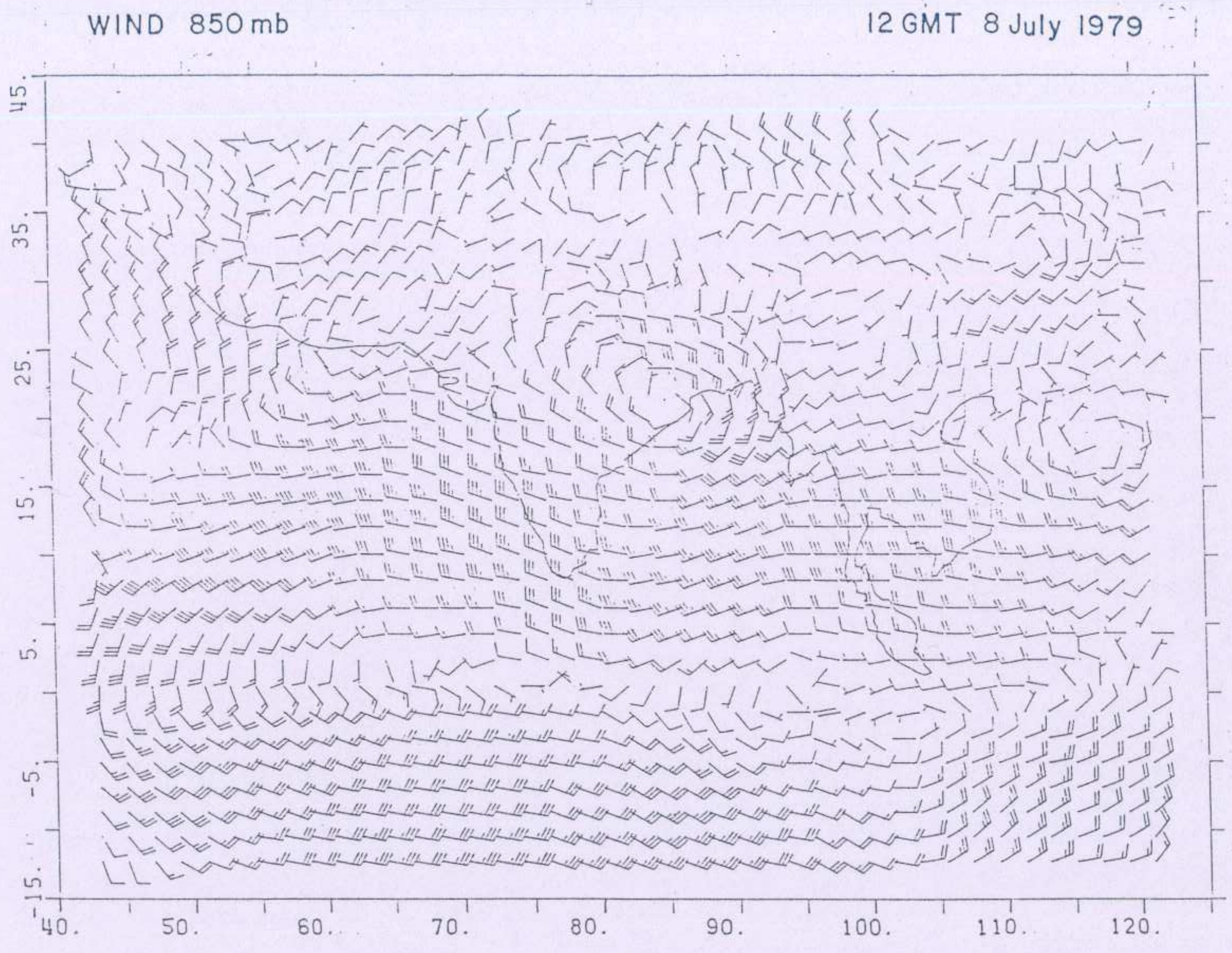

Fig.6b : 850 hPa wind field on 12 GMT 8 July 1979

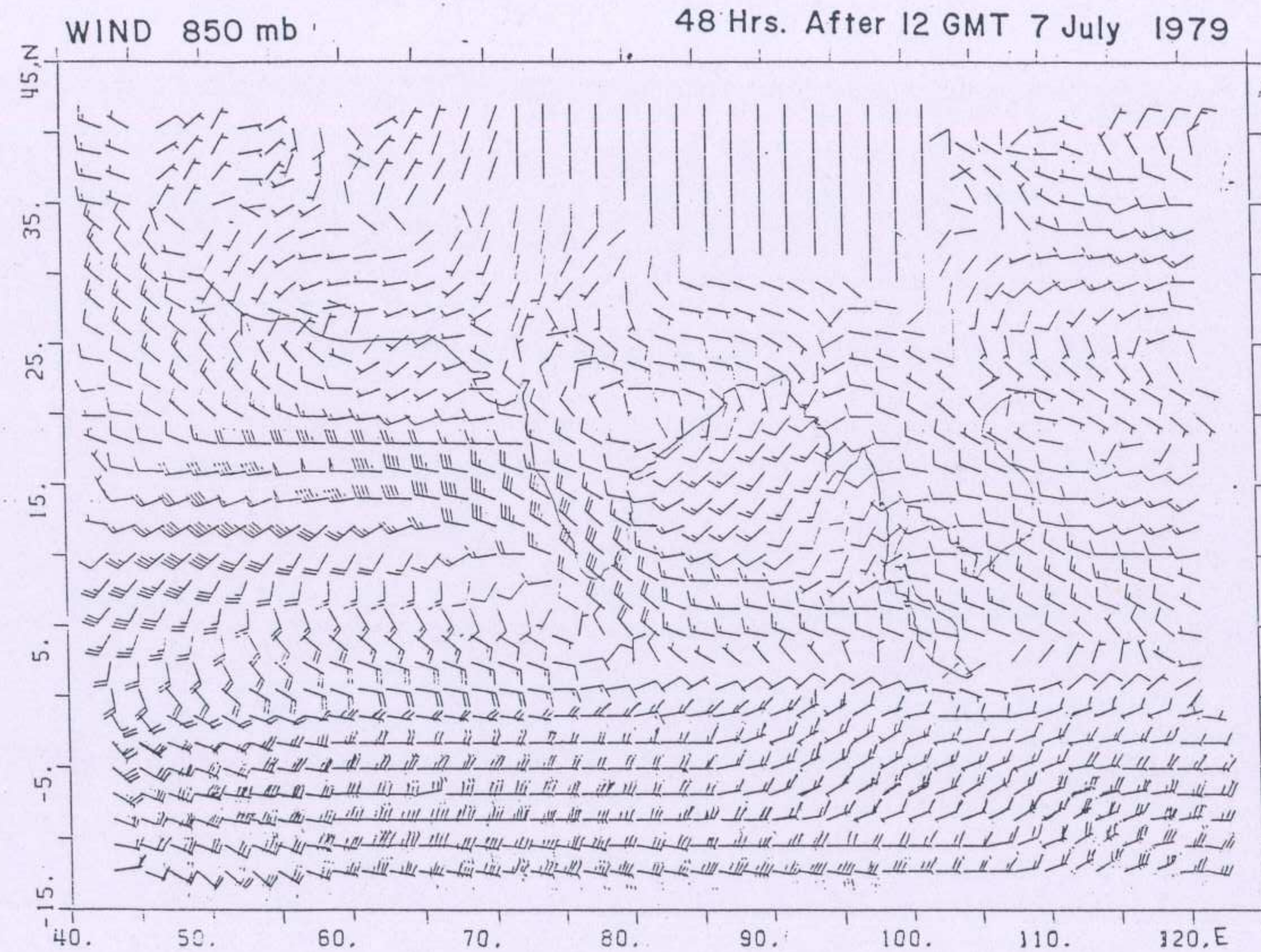

Fig. 6c : 48 hr predicted wind field at 850 hPa

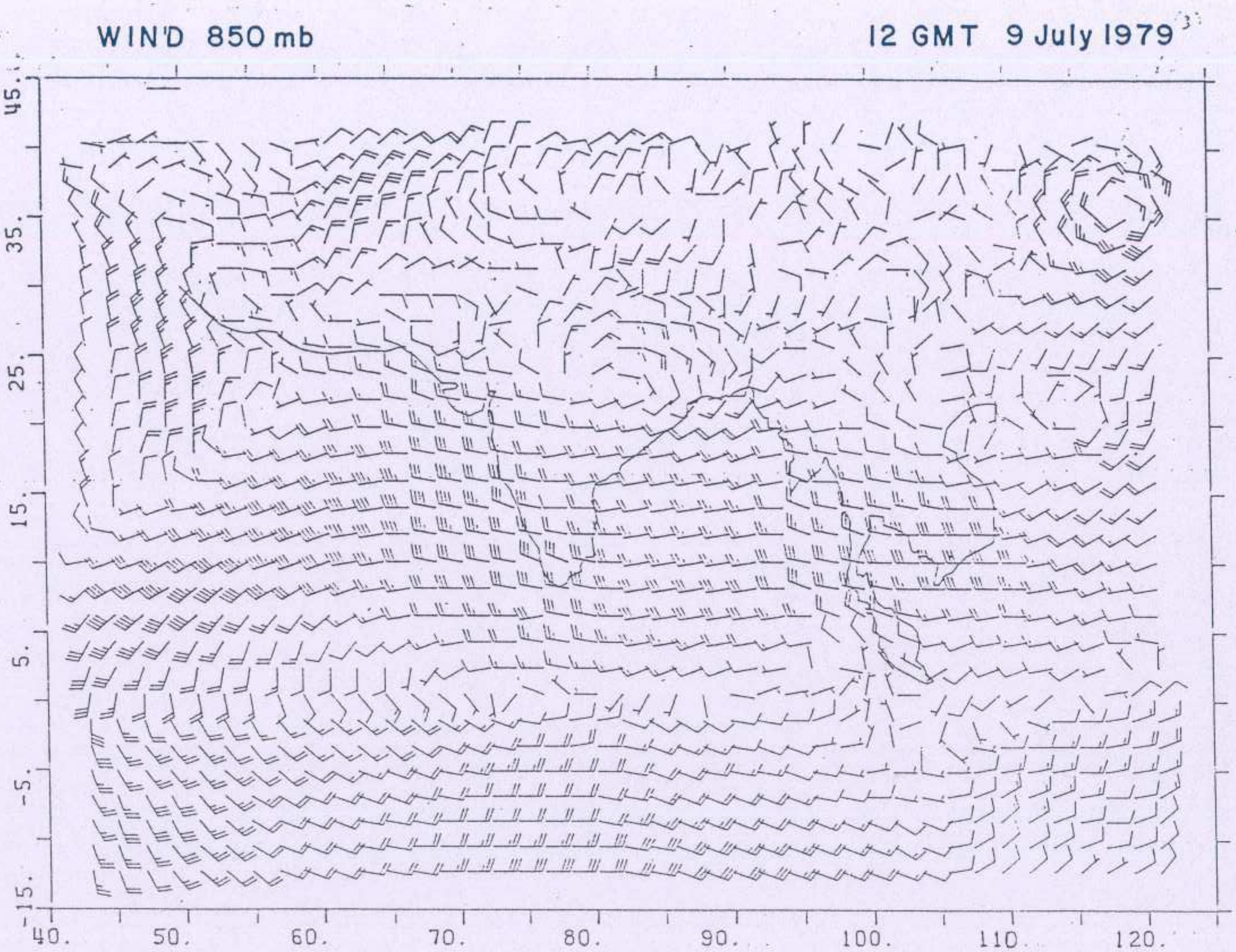

Fig. 6d : 850 hPa wind field on 12 GMT 9 July 1979

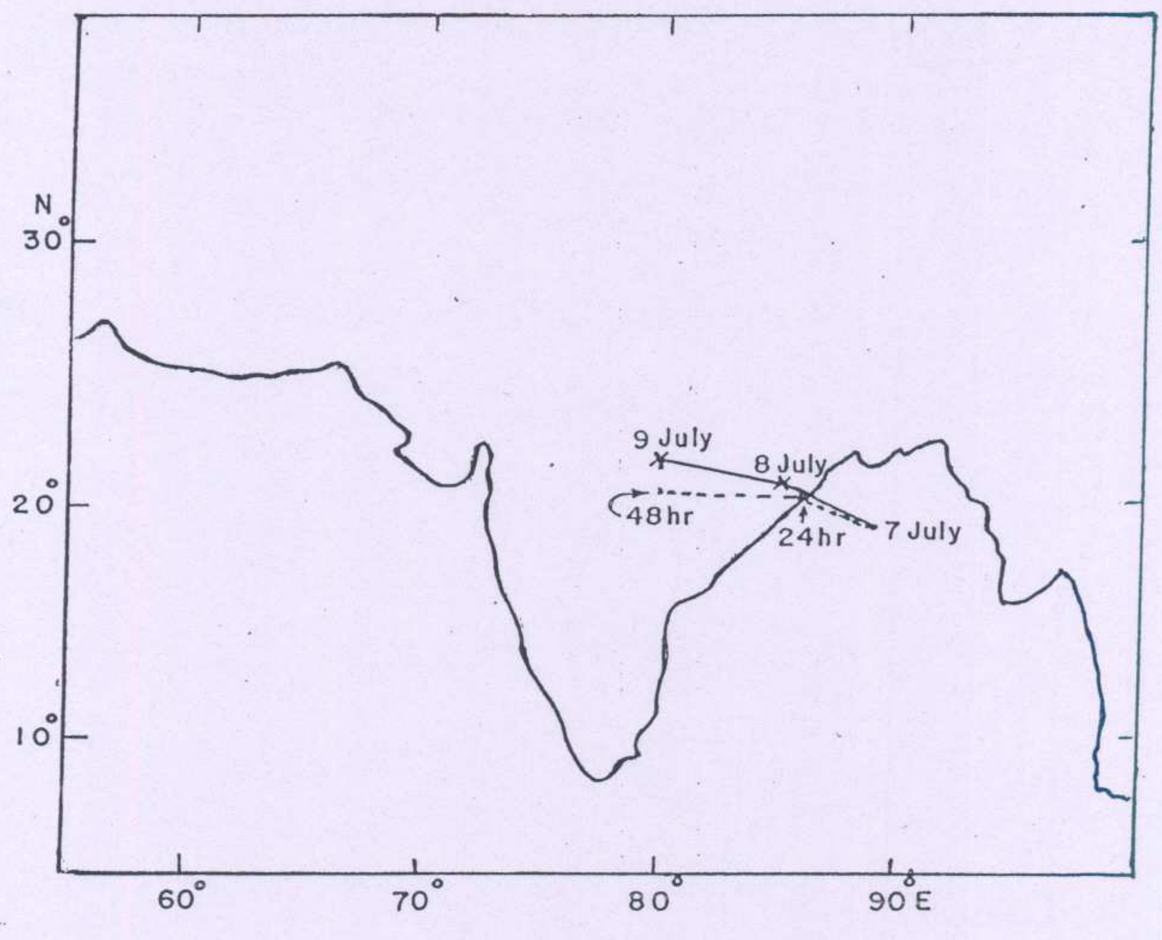

Fig. 7 : Predicted (----) and observed (-) track of the monsoon depression.

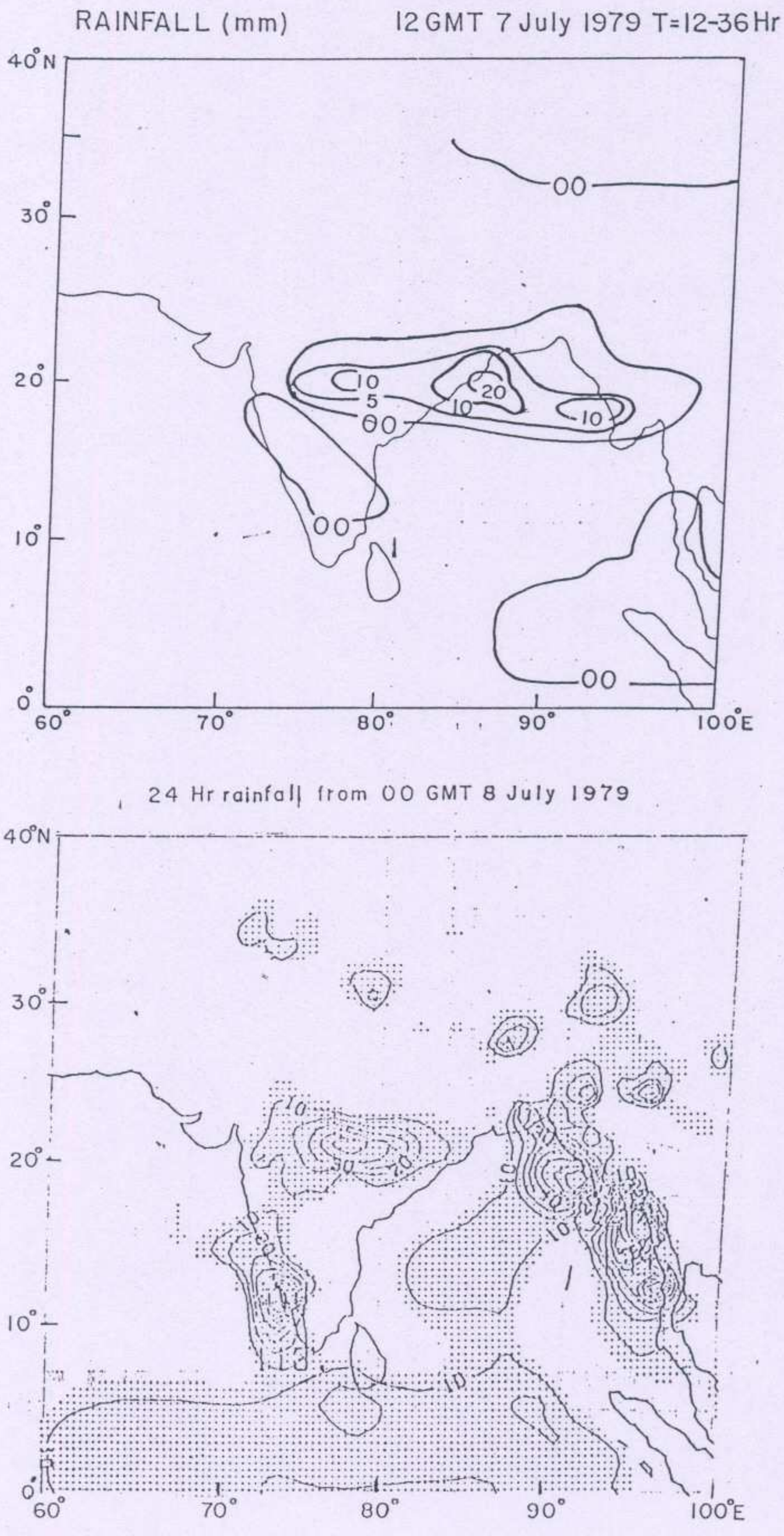

Fig. 8 : Predicted and observed rainfall rates (mm/day).

Definition of variables

IM	Number of grid points in E-W direction
JM	Number of grid points in N-S direction
KM	Number of model levels
KWVM	Same as KM
PTOP	Pressure at the top of the model atmosphere in hPa
RRL	Large scale rainfall in mm/day
RRC	Convective rainfall in mm/day
RRR	Total rainfall mm/day
DELSIG	$\Delta\sigma$ values
SIG	σ values at dotted levels
SIGML	σ values at continuous levels
DELS	Grid distance in x/y direction in mts
IKUO	Index to include parameterization of cumulus convection
NORAD	Index to include simulated radiation
CONS(1)	= 0.8
CONS(2)	= 0.81 critical R.H. values
CONS(3)	= 99.9 maximum value of temperature in ^{o}C above which computations are aborted
KONS(1)	=2 number of level below which large scale heating is computed
IMAX	same as IM
JMAX	same as JM
IJMAX	Total number of grid points in horizontal domain

KMAX	same as KM
KMAXM	KM-1
CL	Latent heat of vaporization 25.1208×10^5 Joules Kg^{-1}
CP	Specific heat at constant pressure 1004.6 Joules $Kg^{-1}{}^oK^{-1}$
GRAV	Accelaration due to gravity 9.8 ms^{-2}
GASR	Gas constant R 287.04 Joules $Kg^{-1}{}^oK^{-1}$
AKAPPA	R/CP (= 0.286)
SIGKUO	same as SIG
SIGKAP	σ^{R/C_p}
SIGKIV	$1/\sigma^{R/C_p}$
DELSGK	$\Delta\sigma$
KTSTAR	Starting time of integration in hours
KTEND	Time in hours for which forecast is needed
FLAT	Latitude valus in degree
FLONG	Longitude values in degree
F	Coriolis parameter
XM	Map factor m (one dimensional)
SM	Same as XM but two dimensional
DELT	Time step for marching in time in sec
DELT2	2*DELT
NSTEP	Number of time steps required in one hour
ISTEP	Total number of steps for the integration from KTSTAR to KTEND

FB	Same as F but at vector points
SM2	m**2
RSM2	1/SM2
RSMB	1/m at vector points
RSMB2	1/m**2 at vector points
DMX	$\partial m/\partial x$
DMY	$\partial m/\partial y$
SMB	Same as SM but at vector point
SINCLT	1/m (one dimensional)
TSEA	Sea temperature in ^{o}C
QSEA	Saturated mixing ratio at TSEA in gm/Kg
PS	Surface pressure in hPa
ZPFM	Geopotential height at pressure levels in mts
PHIS	Orographic height in m^2s^{-2}
PAI	π values in hPa
U	Zonal wind component in ms^{-1}
V	Meridional wind component in ms^{-1}
PT	Potential temperature ^{o}K
WV	Mixing ratio gm Kg^{-1}
DPHI	Geopotential values at σ levels m^2s^{-2}
QQ	This includes all variables U,V,PT, WV and PAI at time t
QQP	same as QQ but at time $t-\Delta t$
QQMT	Tendencies for U,V,PT,WV and PAI
TFCNST	Asselin time filter values
WVM	WV at previoustime step in gm Kg^{-1}

KMPBL	Number of levels upto which PBL parameterisation is applied
SL,SL1	Land-sea indices at scalar and vector points
ROA	$\rho g / \pi \Delta\sigma$
ROB	$\rho^2 g / \pi \Delta\sigma$
A	Used as working space
B	Used as working space
C	Used as working space
WA	Used as working space
WB	Used as working space
WC	Used as working space
WD	Used as working space
W1	Used as working space
W2	Used as working space
W3	Used as working space
W4	Used as working space
W5	Used as working space
W6	Used as working space
W7	Used as working space
W8	Used as working space
PK	T/θ values
S	$\dot{\sigma}$ vertical velocity in sec^{-1}

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