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Operational numerical weather prediction in India — A review

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1. Introduction

The weather and climate, particularly during the monsoon season play an important role in determining the status of Indian economy through their influence on agriculture and water and energy management projects. The prediction of weather, particularly that of rainfall on various space and time scales is, therefore, very important for the planning of agriculture and water management projects. On this account the weather forecasting has been the primary activity of the India Meteorological Department from the very beginning. Mainly two types of weather forecasts are being issued on operational basis, *e.g.*, (*i*) the short-range forecast of various weather elements up to 2-3 days, and (*ii*) long-range (seasonal) forecast of overall monsoon and winter rainfall. The long-range forecast is based essentially on statistical methods while short-range forecast has till recently been based on synoptic considerations.

The synoptic method of short-range weather forecasting involves subjective assessment of the evolution of weather systems in the near future from the study of surface and upper air weather charts. The method of forecasting relies heavily on the current state of the weather, its persistence and climatology of synoptic systems. Where possible, the principles of atmospheric physics are also used in assessing the evolution of weather systems. But, such assessment takes into account only linear effects of dynamical and thermodynamical forcings to a limited extent in a qualitative way. The effect of non-linear and feed-back processes, so important in weather prediction cannot be taken into account. In the absence of any quantitative calculations, the application of physical principles is essentially through empirical "thumb rules". The synoptic method being the subjective one, the weather forecasts from the same initial data by different forecasters may differ greatly; the accuracy of forecast depending much upon the experience of forecaster and his knowledge of local climatology. *Inspite of these limitations*, the synoptic method has been the only effective method of weather prediction till the early fifties. With the advent of electronic computers and their applications in the field of meteorology, numerical methods of weather prediction based on physical principles governing atmospheric motion were developed. These objective methods of weather analysis and prediction based on sound principles of physics and mathematics have shown continuous improvement in the forecast skill over the years.

Numerical Weather Prediction (NWP) is an initial-boundary-value problem to predict the future state of the atmosphere from a given current state based on the fundamental laws of conservation of momentum, conservation of mass, conservation of energy, conservation of water vapour and conservation of other gaseous and aerosol material in the atmosphere.

The mathematical equations govern these principles for a coupled set of equations that must be simultaneously satisfied to form a numerical weather prediction model. Some components of these equations are direct function of parameters like wind, temperature, pressure, etc recorded during routine meteorological observations. The other components like frictional effects, diabatic heating and evaporation and condensation of water vapour are not measured directly and are parametrized suitably in terms of routine meteorological parameters. For prediction of large-scale atmospheric flow on short and medium scales, the effect of gaseous and aerosol material is unimportant. In some simple models, the precipitation processes are also often not considered and principle of conservation of water vapour is not taken into account. Although, designing a numerical weather prediction model is not very difficult, the actual integration of model equations involves many difficulties. Firstly, the model equations are non-linear and do not yield an analytical solution. It is, therefore, necessary to resort to computer oriented numerical methods to obtain their appropriate solution. This is also not an easily tractable problem. The numerical solutions are dependent to a great extent on the choice of boundary conditions and finite differencing methods, which should be chosen very carefully. Besides slow moving synoptic-scale waves, the solution of these equations also contain high frequency sound and gravity waves. Unless proper care is taken to filter out these unwanted high frequency modes, they may foul the required meteorological solution. Over the years many mass and energy conserving and computationally efficient and stable numerical schemes have been developed for integration of sophisticated multi-level models both for operational forecasting and general circulation studies.

Besides a prediction model, an operational numerical weather prediction (NWP) system, needs an efficient data acquisition and analysis system to provide initial input to the forecast model. A system to interpret the model forecast results and to disseminate them to users is also necessary. The computational and technical man-power requirements of an operational NWP system are, therefore, much more than those of a purely research group engaged in numerical modelling activities.

2. Early developmental work

In India, the application of computers for meteorological data processing and analysis started in early sixties during the International Indian Ocean Expedition (IIOE) with an IBM-1620 computer. After the conclusion of the IIOE, this computer was utilised for research and data processing by the Indian Institute of Tropical Meteorology and the India Meteorological Department at Pune. Though IBM-1620 is a small digital computer, it provided very useful initial experience to Indian meteorologists in the use of computers. With the availability of IBM-360/44 computer at the University of Delhi and CDC-3600 computer at the Tata Institute of Fundamental Research, Bombay, two groups — one at New Delhi and the other at Pune got engaged in developmental work in numerical weather prediction. After experimenting with barotropic models and some diagnostic studies for two to three years (Datta and Mukerji 1972 ; Shukla 1972), the work on filtered multi-level model was started. However, due to non-availability of a dedicated in-house computer, the pace of the progress was rather slow. With the installation of a dedicated computer, IBM-360/44 at the India Meteorological Department, New Delhi in July 1973, the work in this field progressed fast. Computer programmes for objective analysis of meteorological data (Rao *et al.* 1972; Datta and Singh 1973) and short-range prediction of flow patterns in the troposphere by a multi-level quasi-geostrophic model (Mukerji and Datta 1973; Ramanathan and Bansal 1976) were developed and put in experimental operational use. With the installation of a data switching computer DS-714 at India Met. Dep., New Delhi towards the end of 1975, the data reception and its direct storage on magnetic tapes became very fast. This cut down the time required for preparation and analysis of data by three to four hours using objective data analysis schemes.

3. Operational Numerical Weather Prediction

The operational numerical weather forecasts are being made by the India *Met. Dep.* at the Regional Meteorological Centre (RMC), New Delhi. The operational numerical weather prediction system has a number of distinct components, *e.g.*,

— Data reception
— Data processing and quality control
— Data analysis
— Forecast model including data initialization
— Interpretation of forecast products
— Dissemination of forecast products.

Their current status at RMC, New Delhi is described below briefly :

3.1. *Data reception*

The collection and dissemination of meteorological data are done through national and international telecommunication networks. New Delhi is the main centre for this where Meteorological Communication Centre (MCC) and Regional Telecommunication Hub (RTH) are located for national and international data exchanges respectively. Since 1976, the data exchange at RTH, New Delhi has been automated through a Phillip DS-714 computer.

RTH, New Delhi is an important centre in the global telecommunication system, exchanging about 12 megabytes of meteorological information daily. Automated in March 1976, this centre is now connected to 11 international centres namely, Tokyo, Moscow, Jeddah, Melbourne, Tehran, Karachi, Cairo, Colombo, Bangkok, Kathmandu and Dhaka with data exchange rates varying from 2,400 bauds (bit per second) to 50 bauds. Tokyo-New Delhi medium speed 2,400 bauds links supplies data from China and Japan. Moscow-New Delhi (2,400 bauds) circuit provides data from Russia, Europe and North America. Bangkok-New Delhi (50 bauds) and Melbourne-New Delhi (75 bauds) circuits provide data from Far East, Pacific region and southern hemisphere including Antarctic region while Cairo (50 bauds), Jeddah (200 bauds), Tehran (50 bauds) links provide data from the Middle-East and Africa. Rest of the circuits like Karachi, Kathmandu, Colombo and Dhaka are the sources for data from neighbouring Southeast Asian region.

The domestic data collection from over 5,000 observatories and their retransmission follow a three-tier system: (*a*) from observatories to the nearest Regional Collecting Centre (RCC), (*b*) from RCC to the Regional Centre (RCs) and to RTH, New Delhi simultaneously, and (*c*) from RTH to the different forecasting offices of the country. For this purpose we use dedicated teleprinter circuits, wireless telegraphy, radio teletypes (RTT), facsimile receivers, telex connections, landline weather telegraphy, radio telephone and even telephones.

On receipt of the data at the RTH, New Delhi basic format checks are employed on all types of bulletins. In addition to this format checking, text processing is done on Indian data for validation and correction. More than a dozen checks are thus imposed on the data before they are ready for transmission to output circuits and also to the processing computer (IBM-360/44).

3.2. *Data processing and quality control*

Coded messages received through GTS often have various types of errors like the observational errors, coding and formating errors and errors which may occur during telecommunication. The coded messages are sorted out and checked for their location and time of observation. The format of the messages are then checked and corrected as far as possible. Most common formating errors are the occurrence of alphameric characters in place of digits, splitting of coded groups and/or combination of groups. The messages are then decoded and various meteorological elements checked for their overall consistency to provide an internally consistent data set for further analysis. The data processing and quality control procedure developed at RMC, New Delhi (Saxena *et al.* 1975) have been improved further to meet FGGE and MONEX data processing requirements also. The data consistency checks used fall broadly in the following categories :

(*i*) *Interconsistency* of different weather elements, like,

- dew point temperature not higher than dry bulb temperature,
- wind direction not exceeding 360°,
- consistency between weather and visibility and weather and cloud cover etc,
- consistency between total cloud amount and and individual cloud amounts.

(*ii*) *Time consistency*

Various weather elements are then compared with data for the previous day or the analysis for the corresponding hour. Those elements which show changes more than acceptable limits are printed out and scrutinised for possible errors keeping in view the prevailing synoptic situation.

(*iii*) *Climatological consistency*

The decoded data are compared with their climatological values. The data which depart from their climatological values by more than acceptable limits are printed out, checked and corrected where possible.

(*iv*) *Horizontal consistency*

The data of a station are also compared with the data of neighbouring stations. The data with large differences from the neighbouring data are checked for possible errors.

(*v*) *Vertical consistency*

The most important check for the upper air data the vertical consistency check. The geopotential an temperature values of the upper air messages are ch cked for hydrostatic balance. Data showing departur from the hydrostatic balance of more than acceptab limits are printed out and corrected where possibl The vertical consistency of wind speed and directic is also checked for sharp changes in wind speed an direction and doubtful data singled out for correctior where possible.

After the above checks the data are machine plo ted and visually examined for any errors and correcte where possible. In addition, the non-conventional meteorological data like,

- Satellite derived winds, temperature and contour heights,
- Satellite inferred location and intensity of synoptic systems,
- Aircraft winds and any other special data

are also incorporated as 'bogus' data at appropriate location at the nearest observation time.

A fairly satisfactory system has been developed for processing of upper air data. More work is in progress for improving the data processing procedures, particularly for the surface and satellite derived observations.

3.3. *Data analysis*

The data received at RMC, New Delhi through GTS are from irregularly spaced observing stations. For integration of the equations of numerical weather prediction models it is necessary to have data on regularly spaced grid points. The process of interpolating data from irregularly spaced observing stations to regularly spaced grid by machine methods is called objective analysis. There are many methods for the objective analysis. At the RMC, New Delhi, the two methods which are presently in operational use are :

(*i*) Objective analysis by Cressman's method, and

(*ii*) Objective analysis by polynomial fitting.

The first method is used for objective analysis of the contour height field at upper levels and the second one for wind analysis at these levels.

(*i*) *Cressman's method of successive correction*

The objective analysis scheme used for the analysis of contour height field is developed by Sinha *et al.* (1982) by following Cressman (1959). The input to the objective analysis programme consists of the analysis for the previous day as an "initial guess" and the current data from the observing stations as obtained after data processing and necessary quality control. The previous day's analysis as "initial guess" is useful in providing time continuity in the analysis scheme. It also provides guess data in the data sparse region without which the analysis is not possible in such areas. In addition to the routine upper air data, necessary information on the location and intensity of centres of lows and highs inferred through satellite observations or through any other special observations over the data sparse regions is provided as "bogus" data. This man-machine-mix in correcting the doubtful observations and supplementing data is necessary for obtaining a good objective analysis.

The observed values of geopotential Z_{os} at the observing stations and the guess interpolated Z_p at the stations are compared and differences for all the stations within the area of influence are obtained. The value of the geopotential guess is obtained through linear interpolation from guess values at grid points around.

Thereafter the following corrections to be applied to the grid point guess are worked out :

$C_1 = W(Z_{os} - Z_p)$ for contour observations only

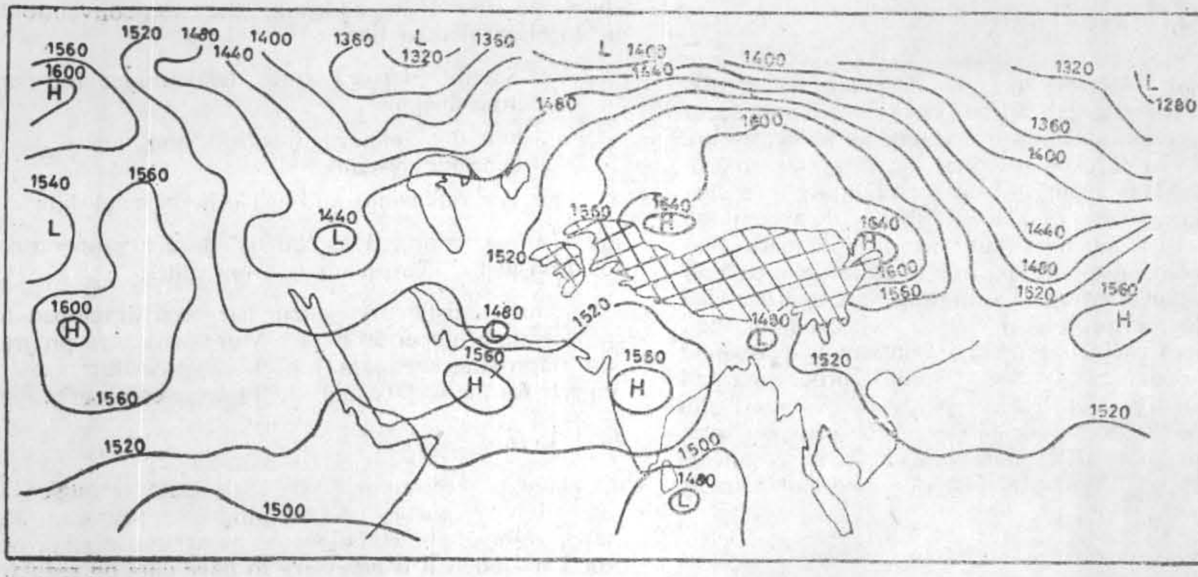

Fig. 1. Objective analysis of contours for 850 mb at 00 GMT of 23 January 1987

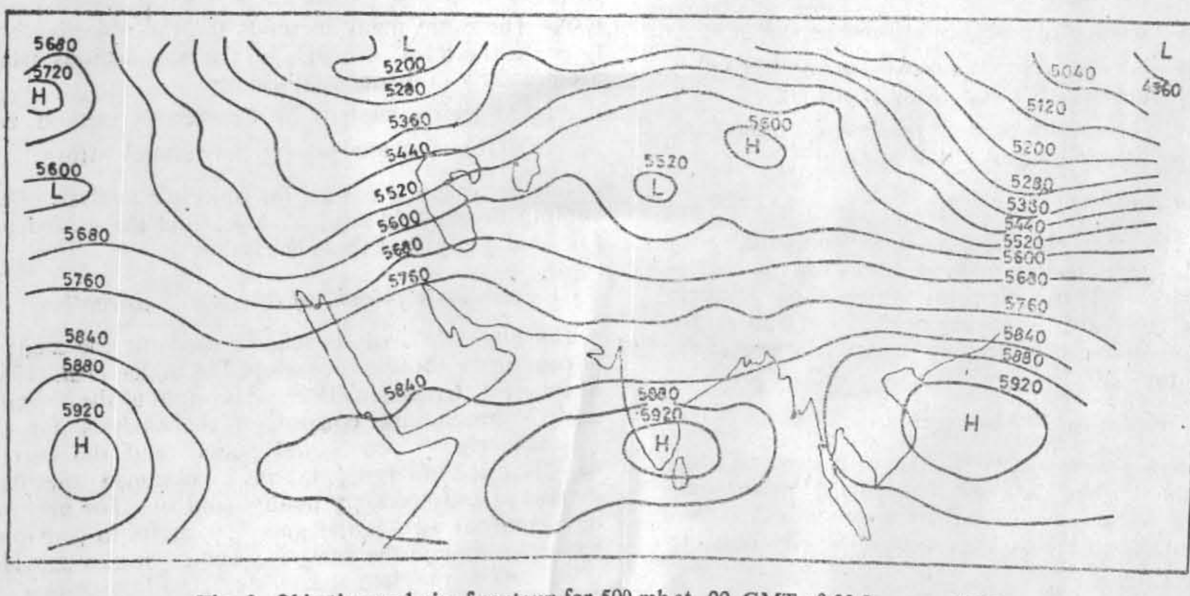

Fig. 2. Objective analysis of contours for 500 mb at 00 GMT of 23 January 1987

$C_2 = W[Z_p - (kf/g)\,(v\triangle x - u\triangle y) - Z_g]$ for wind observations only

$C_3 = W[Z_{os} - (kf/g)(v\triangle x - u\triangle y) - Z_g]$ for wind and contours both,

The weighting function W is defined as :

$$W = (R^2 - D^2)/(R^2 + D^2)$$

and k is a correction for ageostrophy.

Total weighted average correction from all the observations within the area of influence which is finally applied to the grid point guess to obtain the final analysis is

$$C = \frac{(A_1\Sigma C_1 + A_2\Sigma C_2 + A_3\Sigma C_3)}{A_1N_1 + A_2N_2 + A_3N_3}$$

A's are the weights attached to various types of observations and N's the number of observations.

The analysis is made in five successive scans with circular scan radii of 12.6, 10.6, 7.8, 4.8 and 3.5 degrees in a decreasing order. A mild smoother to geopotential field is applied after last two scans. The analysis is done of the 00 and 12 GMT geopotential height fields at 850, 700, 500, 300 and 200 mb providing analyse field at 2.5°Lat./Long. grid over the area 0° to 140°E and equator to 60°N. Human intervention often proves valuable in ensuring the vertical consistency and proper definition of synoptic systems during the analysis. The average root-mean-square errors of the analysis against observed values at reporting stations are of the following order :

850 mb	6.5 gpm
700 mb	7.0 gpm
500 mb	10.0 gpm
300 mb	20.0 gpm
200 mb	26.0 gpm

Using the same method contour height analysis at 2.5° Lat./Long. grid is also done once a day at 00 GMT for 500 mb over the complete latitudinal belt between 0° and 60°N. Sample objective analyses may be seen in Figs. 1 and 2.

(*ii*) *Method of polynomial fitting*

The objective analysis of upper wind is done by fitting a polynomial by the method of least square. The total wind at observing stations is decomposed into zonal and meridional components and each component is analysed separately as a scalar. Finally the analysed components at each grid point are combined to give resultant wind speed and direction. The polynomial used for the analysis is a two-dimensional second degree surface with its centre at the grid point under analysis:

$$H_s = \sum_{jk} a_{jk}\, x^j y^k \;;\; j \geqslant 0,\; k \geqslant 0 \text{ and } j + k \leqslant 2$$

In addition to observed winds, the geostrophic winds from contour height analysis with reduced weights are also used during the analysis. The analysis is done for the wind field at 850, 500 and 300 mb at 00 and 12 GMT on operational basis for the areas 5°-45°N and 40°-140°E at 2.5 Lat./Long. grid. The analysed field compare well with the hand analysis except near the zones of strong wind shear like jet regions. The divergence and vorticity fields calculated from objectively analysed wind show fairly smooth pattern. The average root mean square error of wind analysis is of the order of 20° or less for wind direction and of 4-9 knots of wind speed.

3.4. *Numerical weather prediction model*

Three types of prediction models are in use at the RMC, New Delhi, *viz.*,(*i*) a quasi-geosptrophic five-level model, (*ii*) quasi-geostrophic barotropic model and (*iii*) a primitive equation model. These are limited area models to predict tropospheric flow patterns. On account of the present limitations of the computing facilities, the horizontal and vertical resolution of the models is rather coarse. The models also do not yet include precipitation physics. A brief description of the two models is given below :

(*i*) *Quasi-geostrophic multi-level model*

Since 1973, a multi-level quasi-geostrophic model is in use to prepare 24 hours forecast (Mukerji and Datta 1973; Ramanathan and Bansal 1976). Initially the vertical extent of the model was upto 200 mb with four vertical layers. Now it has been extended to 100 mb with five vertical layers. Since last one years forecast upto 48 hours are being prepared using this model. The horizontal resolution of the model is 2.5°Lat./Long. covering area from 40°E to 120°E and 2.5°N to 42.5°N.

The basic equations for the model are the quasi-geostrophic vorticity equation and the Omega equation:

$$\frac{\partial}{\partial t}\left(\frac{g}{f}\;\nabla^2 z\right) = -\,\mathbf{V}_g\cdot\nabla\eta_g + \bar{f}\,\frac{\partial\omega}{\partial p} \qquad (3.4.1)$$

$$\bar{\sigma}\,\nabla^2\omega + \frac{\bar{f}}{g}\frac{\partial^2\omega}{\partial p^2} = \frac{\bar{f}\partial}{g\partial p}\left(\mathbf{V}_g\cdot\nabla\eta_g\right) - \nabla^2\left(\mathbf{V}_g\cdot\nabla\,\frac{\partial z}{\partial p}\right) - \nabla^2\dot{Q} \qquad (3.4.2)$$

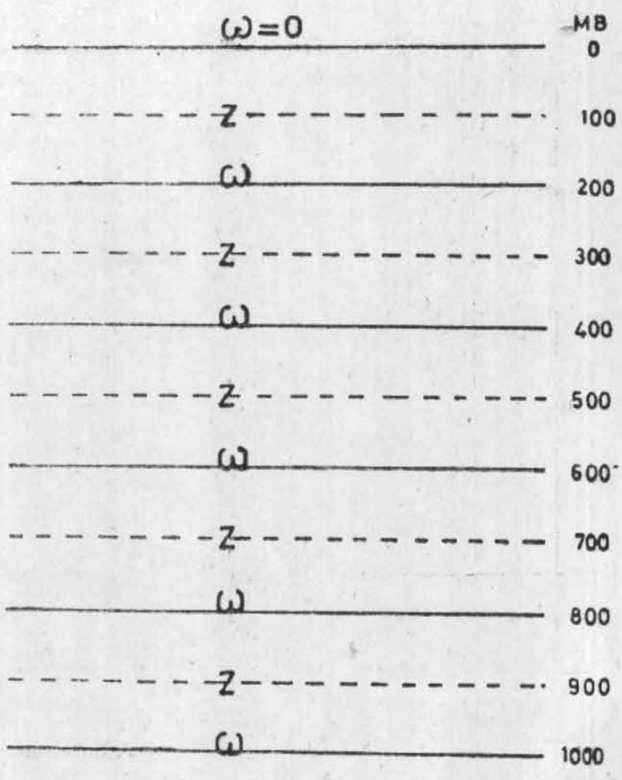

Fig. 3. Vertical resolution of quasi-geostrophic five-level model

Here $\mathbf{V}_g$ and η_g are the geostrophic wind and absolute vorticity, given by

$$\mathbf{V}_g = \mathbf{k}\times\frac{g}{f}\;\nabla z$$

$$\eta_g = \frac{g}{f}\nabla^2 z + f$$

$(g/f)\,\nabla^2 z$ being the relative geostrophic vorticity. The other symbols are :

z = height of the isobaric level,

g = acceleration due to gravity,

f = coriolis parameter, $2\Omega\,\sin\,\phi$; an overbar indicates the average value over the area,

$\bar{\sigma}$ = static stability, a function of p only,

$\omega = dp/dt$: vertical velocity, and

$\dot{Q}$ = non-adiabatic heating rate.

Eqn. (3.4.1) is a prognostic equation to predict geostrophic vorticity and Eqn. (3.4.2) is a diagnostic equation to calculate vertical velocity. The vertical resolution of the model consists of five equi-spaced layers in (x, y, p) co-ordinate system extending from 1000 mb to the top of the atmosphere, *i.e.*, p=0 with structure as shown in Fig. 3. The basic input to the model is the objectively analysed geopotential field at 850, 700, 500, 300 and 200 mb. The working levels of the model are 900, 700, 500, 300 and 100 mb. The geopotential values at 900 mb are obtained by extrapolation on the basis

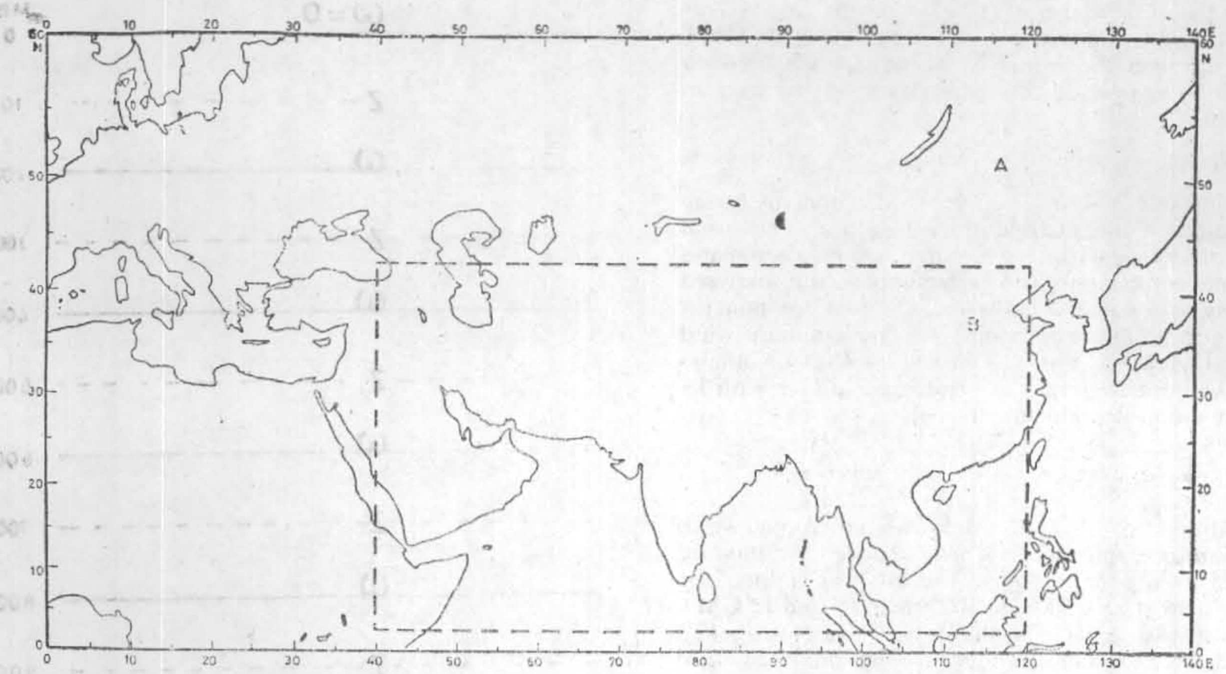

Fig. 4. Horizontal domain for coarse mesh and fine mesh integration of quasi-geostrophic model
A-Coarse mesh, B-Fine mesh

of 700 and 850 mb data. As the actual data at 100 mb is rather scanty, no objective analysis is done for this level at present. Instead, the geopotential at this level is also obtained by extrapolation of data at 200 and 300 mb. The vertical velocity is calculated at 800, 600, 400 and 200 mb. The vertical velocity at the top and bottom of the model is given by the boundary conditions :

$\omega=0$ at the upper boundary, $p=0$ mb

$\omega=\omega_S+\omega_F$ at the lower boundary, $p=1000$ mb

where ω_S and ω_F are topographically and frictionally induced vertical velocities at the lower boundary. The lateral boundary conditions are the pre-assigned values of geopotential and vertical velocity equal to zero at the boundaries.

The model is integrated in two stages, first over the area 0° to 140°E and equator to 60°N with a coarse grid of 5° Lat./Long. and then over the inner smaller area 40° to 120° E and 2.5° to 42.5° N with a finer grid of 2.5° Lat./Long. (Fig. 4). During the first integration the geopotential and vertical velocity, values predicted at each time step over the boundary of the inner smaller area are stored in computer memory. The model is then integrated over the inner area using a finer grid with the geopotential and vertical velocity predicted during the coarse mesh integration as the boundary values at each time step.

The model integration consists of solution of ω-equation (3.4.2) by three dimensional relaxation with suitable over-relaxation factor of 1.3 to obtain vertical velocity at a given time step. The geostrophic wind is calculated from the geopotential which is obtained by two dimensional relaxation of relative vorticity field at individual levels. With the geopotential height (gz), geostrophic wind (V_g) and vertical velocity (ω) thus obtained, the right-hand side of equation (3.4.1) is calculated using finite differences to obtain time tendency of relative vorticity. These tendencies are used to calculate vorticity at the next time level. The process is repeated till 24-hour or 48-hour of model integration to obtain 1 or 2 days forecasts. A centred time differencing scheme with first forward step and a time interval of 1 hour is used for time integration of the model.

The forecast product of geostrophic model are geopotential height field at 850, 700, 500, 300 and 200 mb and vertical velocity field at 1000, 800, 400 and 200 mb over the area 40° to 140°E and 2.5° to 42.5°N at a 2.5° Lat./Long. grid. Short range forecasts by this model show skill at the upper tropospheric levels, but the forecast movement of systems is often much slower than the actual. Over the lower tropospheric levels, the forecast is not very satisfactory. The coarse horizontal and vertical resolution of the model is not able to resolve the synoptic systems like depressions off-shore vortices and low level small scale troughs adequately. Above all, the model has inherent limitations arising due to geostrophic assumption and also does not include physical processes like precipitation and radiation. Nevertheless, the forecasts prepared by the model provide advisory for general as well as for aviation purposes in terms of flow patterns, vertical velocity and temperature fields. The following table provides verification of RMSE of India Meteorological Department quasi-geostrophic model for 850 and 200 mb levels :

Level (mb)	*U (kt)*	*V (kt)*	*Resultant wind (kt)*
850	10.2	8.5	13.3
200	14.0	16.0	25.0

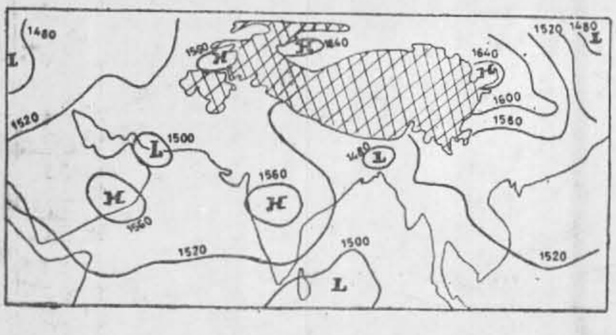

Fig. 5. Quasi-geostrophic model 24 hours forecast for 850 mb valid for 00 GMT of 24 January 1987

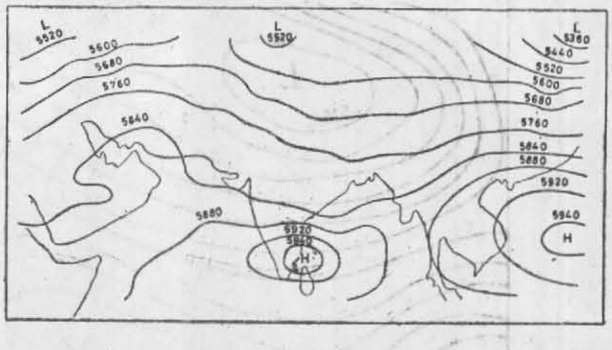

Fig.6. Quasi-geostrophic model 24 hours forecast for 500 mb valid for 00 GMT of 24 January 1987

A sample 24 hours forecast valid for 00 GMT of 24 Jan '87 for 850 and 500 mb based on quasi-geostrophic model is shown in Figs. 5 and 6. It is seen that results are quite satisfactory.

(*ii*) *Global belt barotropic model*

A global belt quasi-geostrophic divergent barotropic model with terrain and friction is also in routine operational use in RMC, New Delhi. It covers the area around the globe from equator to 60°N. The grid mesh is 2.5° Lat./Long. The input to this model is height of 500 mb level. Everyday, based on 00 GMT analysis of geopotentials, forecasts for 24, 48 and 72 hours are prepared.

The governing equation of the model is :

$$\frac{\partial \zeta}{\partial t} + V_g \cdot \nabla(\zeta + f) - \frac{\mu}{z}\left((\zeta + f)\frac{\partial z}{\partial t} + \left(\frac{\partial \zeta}{\partial t}\right)_m + \left(\frac{\partial \zeta}{\partial t}\right)_f = 0\right.$$

where,

$$\zeta = \frac{g}{f}\nabla^2 z,\ \left(\frac{\partial \zeta}{\partial t}\right)_m = \frac{(\zeta + f)}{(p_s - p_o)} \mathbf{V}_s \cdot \nabla p_s$$

$$\left(\frac{\partial \zeta}{\partial t}\right)_f = \frac{g}{f}\left(\frac{\partial \tau_x}{\partial y} - \frac{\partial \tau_y}{\partial y}\right)\frac{(\zeta + f)}{(p_s - p_o)}$$

$$\tau = C_D\,\rho V_H^2$$

Centred in time and space finite difference schemes are used in this model. Laplacian and Jacobians used are also nine-point operators. Time filter is also used to avoid separation of solutions at adjoining grid points. The time step used is one hour.

The model provides useful information about the movement of large scale systems, particularly the troughs *in the westerlies.* A sample 72 hours forecast of 500 mb contours valid for 00 GMT of 26 January 1987 based on global belt barotropic model is given in Fig. 7.

(*iii*) *Primitive equation model*

A limited area primitive equation model is being run on operational basis since late 1984 to predict 24-hour tropospheric flow patterns based on 00 GMT initial data. The model is based on advective form of primitive equation of motion and uses finite differencing scheme of Shuman and Hovermale (1968) in (x, y, σ) coordinate system.

The basic equations of the model are :

$$u_t = -(uu_x + vu_y + \dot{\sigma}u_\sigma) + fv - (\phi_x + c_p\,\theta\pi_x) + \mu\nabla^2 u \quad (3.4.3)$$

$$v_t = -(uv_x + vv_y + \dot{\sigma}v_\sigma) - fu - (\phi_y + c_p\theta\pi_y) + \mu\nabla^2 v \quad (3.4.4)$$

$$\phi_\sigma + c_p\,\theta\pi_\sigma = 0 \quad (3.4.5)$$

$$\theta_t = -(u\theta_x + v\theta_y + \dot{\sigma}\theta_\sigma) + \dot{Q} \quad (3.4.6)$$

$$p_{\sigma_t} = -\{(up_\sigma)_x + (vp_\sigma)_y + (\dot{\sigma}p_\sigma)_\sigma\} \quad (3.4.7)$$

Here $\sigma = (p - p_T)/(p_s - p_T)$ where p_s and p_T are the pressure at the surface of the earth and the top of the model respectively. Top of the model (p_T) is taken as 200 mb.

$$\pi = (p/1000)^{R/c_p}$$

From the definition of σ we see that $p_\sigma = p_s - p_T$ and is function of (x, y) only. Differentiation of Eqn. (3.4.7) with respect to σ thus gives a diagnostic equation to calculate vertical velocity $\dot{\sigma}$ as :

$$\dot{\sigma}_{\sigma\sigma} = -\{(u_{\sigma x} + v_{\sigma y}) + (u_\sigma\, p_{\sigma x} + v_\sigma p_{\sigma y})/p_\sigma\} \quad (3.4.8)$$

The vertical boundary condition of the model are:

$$\dot{\sigma} = 0 \text{ at } \sigma = 0 \text{ and } \sigma = 1$$

while the horizontal boundary condition consists of $u_t = v_t = \theta_t = p_{\sigma_t} = 0$ at the lateral boundaries.

The variables u, v, θ, p_σ, ϕ, π are located at each grid point in an unstaggered way, while σ is located in the centre of the grid square. In the vertical, u, v, θ are located at the centre of the layer, while ϕ, π and $\dot{\sigma}$ are located at the layer interface. The vertical structure of the model consists of 4 layers. The lowest layer is 50 mb thick, designed to incorporate boundary layer effects. The upper three layers are of equal thickness in σ system. The finite difference scheme provides the time tendency values at the centre

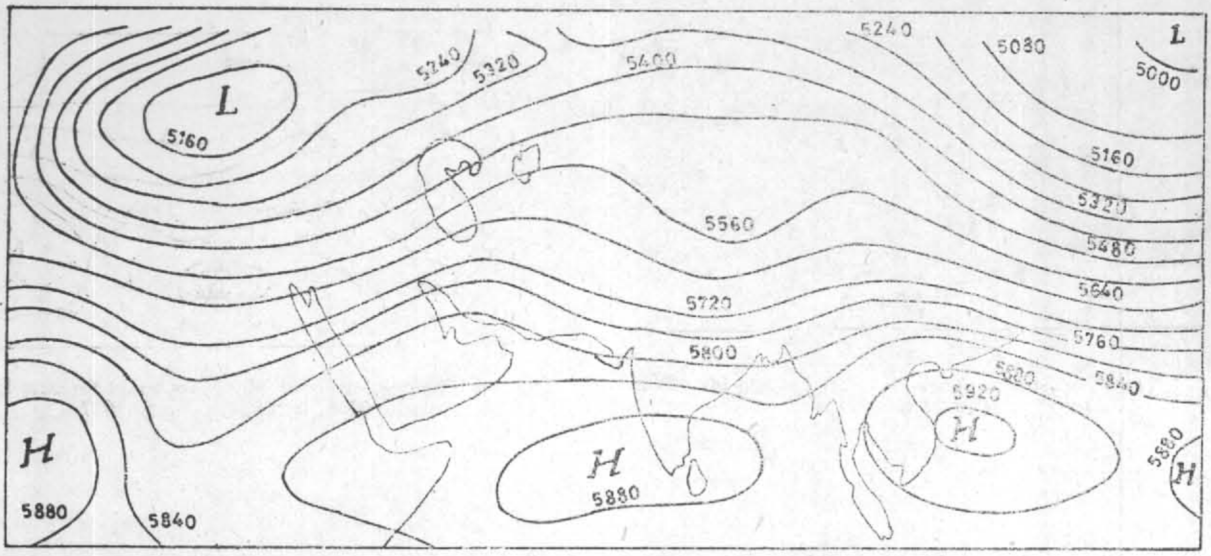

Fig. 7. 72-hr forecast of 500 mb valid for 00 GMT of 26 January 1987 by global belt barotropic model

of the square. As an example, the finite difference form of Eqns. (3.4.3) and (3.4.4) is as below :

$$u_t = -\left(\bar{u}^{xy}\,\bar{u}^{y}_{x} + \bar{v}^{xy}\,\bar{u}^{x}_{y} + \overline{\dot{\sigma}\,\bar{u}^{xy}_{\sigma}}^{\sigma}\right) + f\bar{v}^{xy} - \left(\bar{\phi}^{y}_{x} + c_p\,\bar{\theta}^{xy}\,\bar{\pi}^{y}_{x}\right) + \mu\,\nabla^2\,\bar{u}^{xy} \quad (3.4.9)$$

$$v_t = -\left(\bar{u}^{xy}\,\bar{v}^{y}_{x} + \bar{v}^{xy}\,\bar{v}^{x}_{y} + \overline{\dot{\sigma}\,\bar{u}^{xy}_{\sigma}}^{\sigma}\right) - f\,\bar{u}^{xy} - \left(\bar{\phi}^{x}_{y} + c_p\,\bar{\theta}^{xy}\,\bar{\pi}^{x}_{y}\right) - \mu\nabla^2\bar{v}^{xy} \quad (3.4.10)$$

Here

$$\bar{u}^{x} = \tfrac{1}{2}(u_{i+\frac{1}{2},j} + u_{i-\frac{1}{2},j})$$

$$\bar{u}^{y} = \tfrac{1}{2}(u_{i,j+\frac{1}{2}} + u_{i,j-\frac{1}{2}})$$

$$u_x = (u_{i+\frac{1}{2},j} - u_{i-\frac{1}{2},j})/\triangle x$$

$$u_y = (u_{i,j+\frac{1}{2}} - u_{i,j-\frac{1}{2}})/\triangle y$$

So that

$$\bar{u}^{xy} = \tfrac{1}{4}(u_{i+\frac{1}{2},j+\frac{1}{2}} + u_{i+\frac{1}{2},j-\frac{1}{2}} + u_{i-\frac{1}{2},j+\frac{1}{2}} + u_{i-\frac{1}{2},j-\frac{1}{2}}) \text{ etc.}$$

$$\bar{u}^{y}_{x} = \tfrac{1}{2}[(u_{i+\frac{1}{2},j+\frac{1}{2}} + u_{i+\frac{1}{2},j-\frac{1}{2}}) - (u_{i-\frac{1}{2},j+\frac{1}{2}} + u_{i-\frac{1}{2},j-\frac{1}{2}})]/\triangle x$$

$$\bar{u}^{x}_{y} = \tfrac{1}{2}[(u_{i+\frac{1}{2},j+\frac{1}{2}} + u_{i-\frac{1}{2},j+\frac{1}{2}}) - (u_{i+\frac{1}{2},j-\frac{1}{2}} + u_{i-\frac{1}{2},j-\frac{1}{2}})]/\triangle y \text{ etc.}$$

The average of four tendency values surrounding a grid point provides tendency at the grid point.

The model covers a horizontal area from 0° to 140° E and equator to 60°N with a 2.5° Lat./Long. grid. The lower boundary consists of smoothed topography. The maximum height of the Himalayan topography incorporated in the model is of the order of 5 km.

The basic input to the model consists of surface pressure and the geopotential height at 850, 700, 500, 300 and 200 mb. From the standard isobaric levels the geopotential height is interpolated on σ level. To minimise the error of interpolation, following Phillips (1974), the hydrostatic component corresponding to an isentropic atmosphere is removed from the geopotential at each isobaric level. The deviations of geopotential are then interpolated on σ levels using Lagrange's interpolation formula. The mean potential temperature ($\bar{\theta}$) of the isentropic atmosphere is given by :

$$\bar{\theta} = [<\phi_T> - <\phi_s>]/c_p[<p_s^k> - p_T^k] \quad (3.4.11)$$

and mean geopotential at pressure level (p) is given by

$$\bar{\phi}\,(p) = [<\phi_s>(p^k - p_T^k) - <\phi_T>(<p_s^k> - p_s^k)]/[<p_s^k> - p_T^k] \quad (3.4.12)$$

The subscripts T and s refer to the top (200 mb) and bottom (earth's surface) of model while $<>$ denotes average values.

A similar procedure is adopted while interpolating geopotential heights from σ to p surfaces at the end of model integration.

The data initialization procedure consists of static initialization followed by dynamic initialization. Static initialization consists of calculating the geostrophic wind from geopotential height on σ surfaces. The balance between the wind and mass field consistent with the model equations is then obtained by integrating the model forward for one hour followed by backward integration. At the end of the cycle 50% of the initial pressure and temperature values are restored while the wind field is allowed to change freely. Three such cycles are found sufficient to balance the mass and wind field satisfactorily. Matsuno's forward-backward time integration scheme (Matsuno 1966) is used during data initialization.

The primitive equation model (Bedi *et al.* 1976), was used for number of sensitivities experiments concerning monsoon dynamics (Das and Bedi 1976, 1979, 1981).

The limited area primitive equation model is in experimental operational use since November 1984. A smoothed actual topography is incorporated as the lower boundary condition. Except for dry convective adjustment and diffusive process no physics is yet included in the model. During interpolation from p to σ and σ to p some unacceptable errors occur over the Himalayan region. Inspite of these limitation, the verification results so far show that the performance of primitive equation model is better than the quasi-geostrophic model. The movement of the synoptic systems in primitive equation model forecast though somewhat slower than the actual, is more close to the actual movement than the movement predicted by the quasi-geosptrophic model.

A comparison of 24 hours wind forecast with primitive equation model and observed wind show a good forecast skill much better than the wind forecast skill by quasi-geostrophic model.

A sample 24 hours forecast of 500 mb contours valid for 00 GMT of 24 Jan '87 based on primitive equation model may be seen in Fig. 8.

3.5. *Interpretation of NWP output products*

The operational NWP models used in India Met. Dep. at present do not provide direct forecast of precipitation and other weather elements. It is, therefore, necessary to interpret the NWP output in terms of weather elements of interest. So far sufficient work has not been put in this field. The main reason is that the NWP models are still in developmental stage. Inspite of this some attention has been paid to this aspect also. Datta *et al.* (1976) attempted interpretation of meso-scale weather from synoptic scale flow patterns predicted by NWP models.

3.6. *Dissemination of output products*

Besides, the objective analysis of geopotential height and wind field and 24 and 48-hour forecasts of geopotential heights some more products are being prepared.

They are :

(*i*) Vorticity, divergence and vorticity advection fields from wind analysis,

(*ii*) Thermal wind between 850 and 500 mb levels,

(*iii*) Weekly and monthly means of sea-surface temperatures over Indian seas,

(*iv*) 5-day and 10-day mean geopotential height charts and

(*v*) Mid-latitude zonal index.

The objective analysis, the model forecast and some of the special products are transmitted as advisories to various forecasting offices on radio-facsimile. The current status of various numerical products and their dissemination to other forecasting offices is given under Table 1.

The RMC, New Delhi also receives the analysis and forecast products of ECMWF on regular basis. These forecasts prove useful for the area over which operational limited area models do not extend. Also they provide useful comparison between ECMWF and RMC forecasts.

4. Developmental work

Further developmental work is in progress in various aspects of numerical analysis and forecast. The main areas of developmental work are listed below :

4.1. *Objective analysis of sea level pressure*

At present the mean sea level pressure input to the primitive equation model is the hand analysis of sea level pressure field. Therefore, there is an urgent need for a suitable objective analysis scheme for this field. A scheme based on Gandin's univariate optimum interpolation method is under development for the areas 0° to 60°N and 0° to 140°E. The influence functions used in the analysis have been taken provisionally from other works. The influence functions for the Indian region for various seasons will be worked out later.

4.2. *Humidity analysis*

A scheme for humidity analysis at various levels in the lower troposphere is being developed. The empirical relationships between the humidity at surface level and upper levels are being worked out to maximize upper level humidity input data on the basis of surface observations. The scheme also includes plans to utilize satellite observations to deduce humidity field, which will be of particular use over the data sparse oceanic regions.

4.3. *Global spectral model*

A 5-level primitive equation spectral model is under development at Northern Hemisphere Analysis Centre (NHAC), New Delhi. Before the work on this model was started necessary experience in spectral techniques was gained by integrating a single level hemispheric quasi-geostrophic spectral model (Bedi 1979) and a 3-level primitive equation spectral model (Bedi 1985). The primitive equation spectral model is based on the equations of motion in vorticity and divergence forms in spherical coordinates in the horizontal and sigma coordinates in the vertical. The equations without external forcings and moisture processes are written in the form :

$$\frac{\partial \zeta}{\partial t} = - F(A,B) - 2\Omega(D \sin \phi + v/a) \quad (4.3.1)$$

$$\frac{\partial D}{\partial t} = F(B,-A) + 2\Omega(\zeta \sin \phi - U/a) - \nabla^2 K \quad (4.3.2)$$

$$\frac{\partial T}{\partial t} = - F(P, Q) + H \quad (4.3.3)$$

$$\frac{\partial q}{\partial t} = - \mathbf{V} . \nabla q - D - \frac{\partial \dot{\sigma}}{\partial \sigma} \quad (4.3.4)$$

$$\frac{\partial \phi}{\partial \sigma} = - \frac{RT}{\sigma} \quad (4.3.5)$$

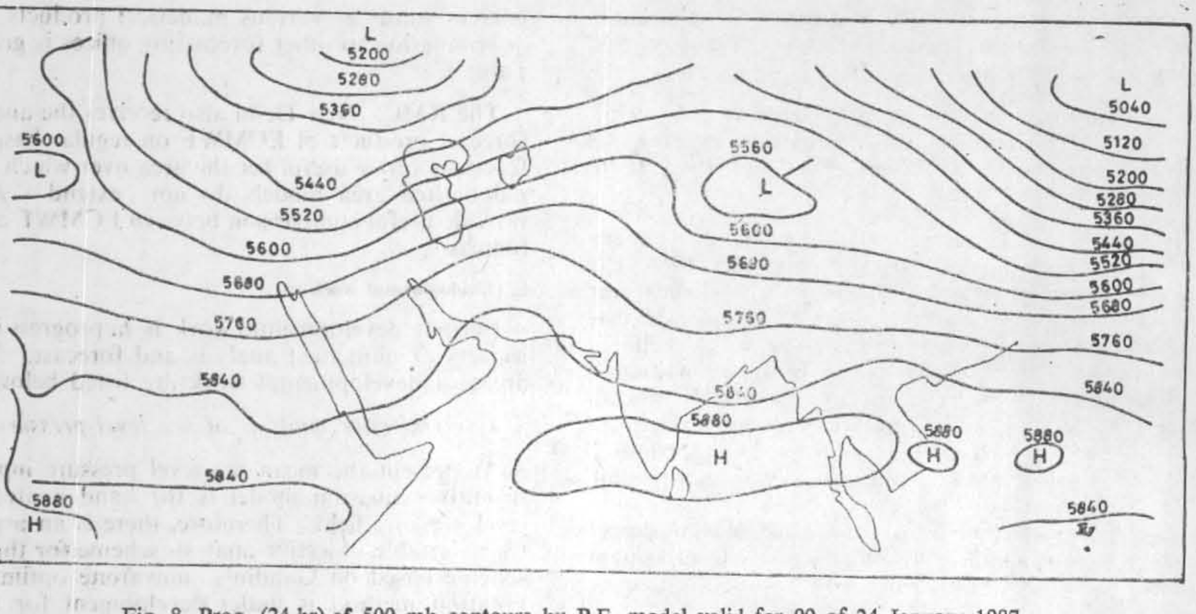

Fig. 8. Prog. (24-hr) of 500 mb contours by P.E. model valid for 00 of 24 January 1987

TABLE 1

Summary of numerical products prepared at Northern Hemisphere Analysis Centre (NHAC)

Product	Synoptic hr (GMT)	Area	Level	Weather transmitted to other forecasting offices
Objective analysis of height field	00 and 12 hr	Equator to 60° N, 0° to 140° E.	850, 700, 500, 300 and 200 mb	No
Objective analysis of wind field	Do.	Do.	700, 500 and 300 mb	No
24-hr forecast of height field	Do.	2.5° to 42.5°N, 40° to 120° E	900, 700, 500, 300 and 200 mb	500, 300 and 200 mb levels transmitted for 00 GMT only
Diagnostic vertical velocity field	Do.	Do.	1000, 800, 600, 400 and 200 mb	800, 600 and 400 mb levels transmitted for 00 GMT only
24-hr forecast of vertical velocity	Do.	Do.	Do.	No
Diagnostic vorticity from wind data	Do.	Equator to 60°N, 0° to 140°E	700, 500 and 300 mb	Transmitted for 00 GMT only
Diagnostic vorticity advection from wind data	Do.		Do.	No
Diagnostic divergence from wind data	Do.	Do.	Do.	No
Thermal winds	Do.	Do.	Between 850 and 500 mb	No
Mean sea surface temp. *i.* Monthly; *ii.* Weekly	Daily; Daily	Equato to 25° N, 55° to 100° E.	Sea surface	Weekly means transmitted once a week (on Tuesday)
5-day and 10-day mean charts	Daily	Do.	700, 500 and 300 mb	No
Mid-latitude zonal index	00 and 12 hr	Betwen latitudes 30° o 50° N and longitude 0° to 140° E.	700 and 500 mb	No

where,

$$A = U\zeta + \dot{\sigma}\,\frac{\partial V}{\partial \sigma} + \frac{RT'}{a}\cos\phi\,\frac{\partial q}{\partial \phi}$$

$$B = V\zeta - \dot{\sigma}\,\frac{\partial U}{\partial \sigma} - \frac{RT'}{a}\,\frac{\partial q}{\partial \lambda}$$

$$H = T'D - \dot{\sigma}\left(\frac{RT}{\sigma c_p} - \frac{\partial T}{\partial \sigma}\right) + \frac{RT}{c_p}\left[\left(\bar{D} + (\mathbf{V}+\bar{\mathbf{V}})\cdot\nabla q\right)\right]$$

$$P = UT'$$

$$Q = VT'$$

$$K = \frac{U^2 + V^2}{2\cos^2\phi} + \Phi' + RT_0\,q$$

$$F(x,y) = \frac{1}{a\cos^2\phi}\left[\frac{\partial \chi}{\partial \lambda} + \cos\phi\,\frac{\partial y}{\partial \phi}\right]$$

ζ and D are the relative vorticity and divergence respectively and q = ln p_s; p_s being surface pressure, Φ is the geopotential. All dashed quantities are deviation from their horizonal mean.

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

$$\dot{\sigma} = \frac{d\sigma}{dt}$$

The vertical boundary conditions are :

$$\dot{\sigma} = 0 \text{ at } \sigma = 1 \text{ and } 0$$

The integration of Eqn. (4.3.4) from σ=1 to σ=0 gives the prognostic equation for surface pressure as :

$$\frac{\partial q}{\partial t} = \bar{\mathbf{V}}\cdot\nabla q + \bar{D} \qquad (4.3.6)$$

A diagnostic equation for $\dot{\sigma}$ is obtained by eliminating $\partial q/\partial t$ between (4.3.4) and (4.3.6) as:

$$\dot{\sigma} = [(1-\sigma)\,\bar{D} - \bar{D}^{\sigma}] + [1-\sigma)\,\bar{\mathbf{V}} - \bar{\mathbf{V}}^{\sigma}]\cdot\nabla q \qquad (4.3.7)$$

Here

$$\overline{(\ )} = \int_1^0 (\ )\,d\sigma \text{ and } \overline{(\ )}^{\sigma} = \int_\sigma^0 (\ )\,d\sigma$$

The above system of equations forms a closed set of equations and is essentially of the same form as used by Daley *et al.* (1976) and Bourke *et al.* (1977). The continuity of velocity field at poles is achieved by using U and V in above equations as :

$$U = u\cos\phi = -\frac{\cos\phi}{a}\frac{\partial \Psi}{\partial \phi} + \frac{1}{a}\frac{\partial \chi}{\partial \lambda}$$

$$V = v\cos\phi = \frac{1}{a}\frac{\partial \Psi}{\partial \lambda} + \frac{\cos\phi}{a}\frac{\partial \chi}{\partial \phi} \qquad (4.3.8)$$

The spectral form of equation is obtained by expanding the variables Ψ, χ, T and q etc in terms of a truncated series of surface spherical harmonics as :

$$\Psi = \sum_{m=-M}^{M}\ \sum_{n=|m|}^{|m|+J} \Psi_n^m\, Y_n^m(\lambda,\phi) \qquad (4.3.9)$$

where, $Y_n^m(\lambda,\phi) = e^{im\lambda}\,P_n^m(\phi)$ is spherical harmonic of order m and degree n. Inserting such representation in above equations, the spectral form of equations is obtained as :

$$\frac{-n(n+1)}{a^2}\frac{\partial \Psi_n^m}{\partial t} = F_n^m(A,\ \beta) - \frac{2\Omega}{a^2}\Big[(n-1)(n+1)\times \beta_n^m\,\chi_{n-1}^m + n(n+2)\,\beta_{n+1}^m\,\chi_{n+1}^m - im\,\Psi_n^m\Big] \qquad (4.3.10)$$

$$\frac{-n(n+1)}{a^2}\frac{\partial \chi_n^m}{\partial t} = F_n^m(B,-A) - \frac{2\Omega}{a^2}\Big[(n-1)(n+1)\,\beta_n^m\,\Psi_{n-1}^m + n(n+2)\,\beta_{n+1}^m\,\Psi_{n+1}^m + im\,\chi_n^m\Big] + n(n+1)\,K_n^m \qquad (4.3.11)$$

$$\frac{\partial T_n^m}{\partial t} = -F_n^m(P,Q) + H_n^m \qquad (4.3.12)$$

$$\frac{\partial q_n^m}{\partial t} = (\bar{\mathbf{V}}\cdot\nabla q)_n^m - \frac{n(n+1)}{a^2}\,\bar{\chi}_n^m \qquad (4.3.13)$$

$$\frac{\partial \Phi_n^m}{\partial \sigma} = -\frac{RT_n^m}{\sigma} \qquad (4.3.14)$$

where,

$$\beta_n^m = \left(\frac{n^2 - m^2}{4n^2 - 1}\right)^{\frac{1}{2}}$$

Spectral components of non-linear terms $F_n^m(A,B)$, $F_n^m(B,-A)$, $F_n^m(P,Q)$, K_n^m, H_n^m, $(\mathbf{V}\cdot\nabla q)_n^m$ are calculated by transform method (Orszag 1970; Machenhauer and Rasmussen 1972) using Fast Fourier Transform and Gausian Quadrature with necessary number of longitude and latitude points.

So far a dry version of the spectral model with option to integrate over the globe or northern hemisphere has been developed. The existing limitations of computing facilities do not permit horizontal resolution of more than 10 zonal waves and 10 zeros in the meridional direction. Vertical resolution is of 5 layers of equal sigma thickness. With the availability of better computing facilities it will be possible to increase the model resolution with small efforts.

Time integration is based on semi-implicit method using 45 minutes time step. As a suitable global data analysis system does not yet exist for all variables, the input to the model is the grid point values of geopotential height field analysed at standard isobaric level.

The spectral components of relative vorticity are calculated from geopotential height components using spectral form of linear balance equation (Bedi 1976). These components are then interpolated on sigma surfaces. The spectral components of geopotential height are also interpolated on sigma level to provide components of temperature field. The model is then integrated forward and backward for 3 cycles of 1 hour each to generate necessary divergence. Thereafter, forward integration of the model is done over the forecast period using semi-implicit time integration scheme.

Preliminary tests show that the model code has no errors. The representation of various synoptic system is proper and their forecast movement is in right direction and of right order. Further work is necessary to incorporate necessary physics and test the model more rigorously.

4.4. *Two level model*

Two level models have also been developed (Sinha 1972). The basic equations are :

(*i*) *Vorticity equation*

$$\nabla^2 \frac{\partial z}{\partial t} + \frac{g}{f} J(z, \nabla^2 z) + \beta \frac{\partial z}{\partial x} - \frac{\bar{f}^2}{g} \frac{\partial \omega}{\partial p} = 0$$

Thermodynamic equation

$$\frac{\partial}{\partial t}\left(\frac{\partial z}{\partial p}\right) + u \frac{\partial}{\partial x}\left(\frac{\partial z}{\partial p}\right) + v \frac{\partial}{\partial y}\left(\frac{\partial z}{\partial p}\right) + \frac{\sigma}{p^2}\omega = 0$$

where the static stability is given as :

$$\sigma = \frac{R^2\, T^2}{g^2\, \theta}\left(\frac{\partial \theta}{\partial z}\right)$$

In this model the vorticity equation is applied to two levels which are 300 and 700 mb and the thermodynamic equation is applied to the in between layer from 700 to 300 mb. Assuming

$$\left(\frac{\partial \omega}{\partial p}\right)_{300\text{mb}} = \frac{\omega_{500\text{mb}} - \omega_{0\text{mb}}}{(500-0)} = \frac{\omega_5}{500}$$

$$\left(\frac{\partial \omega}{\partial p}\right)_{700\text{mb}} = \frac{\omega_{1000\text{mb}} - \omega_{500\text{mb}}}{1000-500} = \frac{-\omega_5}{500}$$

$$z_{500\text{mb}} = \left(z_{300\text{mb}} + z_{700\text{mb}}\right)\Big/ 2 = \bar{z}$$

$$\left(\frac{\partial z}{\partial p}\right)_{500\text{mb}} = \left(z_{700\text{mb}} - z_{300\text{mb}}\right)\Big/ (700\text{ mb} - 300\text{ mb}) = -h/400$$

and with algebraic manupulations we get

$$\nabla^2\left(\frac{\partial \bar{z}}{\partial t}\right) = -\frac{g}{2f} J\left(z, \nabla^2 z\right)_{700\text{mb}} - \frac{g}{2f} J\left(z, \nabla^2 z\right)_{300\text{mb}} - \beta\left(\frac{\partial \bar{z}}{\partial x}\right)$$

$$\nabla^2\left(\frac{\partial h}{\partial t}\right) - \frac{10}{4}\frac{f^2}{g\sigma}\frac{\partial h}{\partial t} = \frac{g}{f} J\left(z, \nabla^2 z\right)_{700\text{mb}} - \frac{g}{f}\left(z, \nabla^2 z\right)_{300\text{mb}} - \beta\frac{\partial h}{\partial x} + \frac{10}{4}\frac{\bar{f}}{\sigma} J(\bar{z}, h)$$

$$\omega_5 = \frac{p^2_{500\text{mb}}}{400\,\sigma}\left[\frac{\partial h}{\partial t} + \frac{g}{f} J(\bar{z}, h)\right]$$

A 2° Lat./Long. grid from 5°N to 30°N and 65°E to 100°E was used. For numerical calculations centred in space, nine-point Laplacian and Jacobian operators were used. Leapfrog time integration scheme with on hour time step is used for integration. Sequential over-relaxation is used for solving the Poisson's equation. Tendencies of z and h at lateral boundaries are assumed to be zero. Omega at top of the atmosphere and at lowest level are also assumed to be zero. This model was found to score favourably over-persistence.

4.5. *Non-linear balance model*

Non-linear balance models were also developed by Sinha *et al.* (1981) and Rao *et al.* (1985). The basic set of equations used in this model are :

(*i*) *Vorticity equation*

$$\frac{\partial}{\partial t}\nabla^2\psi = -J(\psi, \zeta_a) + \nabla\chi\cdot\zeta_a + (\zeta + f)\nabla^2\chi - \omega\frac{\partial}{\partial p}\nabla^2\zeta - \nabla\omega.\nabla\frac{\partial\psi}{\partial p} - g\frac{\partial}{\partial p}\left[\frac{\partial\tau_x}{\partial y} - \frac{\partial\tau_y}{\partial x}\right]$$

(*ii*) *Balance equation*

$$\nabla f.\nabla\psi + f\nabla^2\psi = \nabla^2\phi - 2J\left(\frac{\partial\psi}{\partial x}, \frac{\partial\psi}{\partial y}\right)$$

(*iii*) *Thermodynamic equation*

$$\pi\frac{\partial\theta}{\partial t} = -\pi J(\psi, \theta) + \pi\nabla\chi\cdot\nabla\theta + \sigma\omega + \frac{H_L + H_S}{pc_p}$$

where,

$$\zeta_a = \frac{g}{f}\nabla^2\psi + f\,;\ \pi = RT/p\theta$$

$$\sigma = -\pi(\partial\theta/\partial p)\,;\ \nabla^2\chi = \partial\omega/\partial p$$

The Omega equation of the balance model is :

$$\nabla^2\sigma\omega + f^2\frac{\partial^2\omega}{\partial p^2} = f\frac{\partial}{\partial p}J(\psi,\zeta_a) + \pi\nabla^2\Big[J(\psi,\theta)\Big] + 2\frac{\partial}{\partial t}\frac{\partial}{\partial p}\left[J\left(\frac{\partial\psi}{\partial x}, \frac{\partial\psi}{\partial y}\right)\right] - f\frac{\partial}{\partial p}\left(\zeta\nabla^2\chi\right) + f\frac{\partial}{\partial p}g\frac{\partial}{\partial p}\left[\frac{\partial\tau_y}{\partial x} - \frac{\partial\tau_x}{\partial y}\right] - \frac{R}{pc_p}\nabla^2\Big[H_L + H_S\Big]$$

$$+ f\frac{\partial}{\partial p}\left(\omega\frac{\partial}{\partial p}\ \nabla^2\psi\ \right) + f\frac{\partial}{\partial p}\left(\nabla\omega.\nabla\ \frac{\partial\psi}{\partial p}\right)$$

$$- f\frac{\partial}{\partial p}\ (\nabla\chi\cdot\nabla\zeta_a) - \pi\ \nabla^2(\nabla\chi\cdot\nabla\theta) -$$

$$- \beta\frac{\partial}{\partial p}\frac{\partial}{\partial y}\ \frac{\partial\psi}{\partial t}$$

In the vertical five layers are used and in horizontal a 2° Lat./Long. grid is used. All the finite difference schemes used are centred in space and nine-point Laplacians and Jacobians are used. Sequential over relaxation is used for solving the vorticity and Omega equations.

The following steps are followed for calculations of vertical velocities :

(*i*) The wind vectors are resolved to get zonal and meridional components of wind.

(*ii*) Kinematic vorticity is computed from wind components.

(*iii*) Stream function is obtained by solving
$$\nabla^2\ \psi = \zeta$$
through relaxation with suitable boundary conditions.

(*iv*) Substituting the stream function ψ in the non-linear balance equation, it is solved for geopotential by relexation.

(*v*) Temperatures and hydrostatic stability is calculated through hydrostatic equation for geopotentials.

$$\begin{bmatrix} 1+\epsilon_1^2 & \rho_{12}+\eta_{12}\,\epsilon_1\,\epsilon_2 & \cdots & \rho_{1n}+\eta_{1n}\,\epsilon_1\,\epsilon_n \\ \rho_{21}+\eta_{21}\,\epsilon_2\,\epsilon_1 & 1+\epsilon_2^2 & & \rho_{2n}+\eta_{2n}\,\epsilon_2\,\epsilon_n \\ \vdots & \vdots & & \vdots \\ \rho_{n1}+\eta_{n1}\,\epsilon_n\,\epsilon_1 & \rho_{n2}+\eta_2\epsilon_n\epsilon_2 & & 1+\epsilon_n^2 \end{bmatrix} \cdot \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} \rho_{1g} \\ \rho_{2g} \\ \vdots \\ \rho_{ng} \end{bmatrix} \qquad (5.1.2)$$

(*vi*) Initially assuming ω and χ both to be zero at all points vorticity equation is sloved to get $\partial\psi/\partial t$.

(*vii*) Solve the non-linear balance Omega equation to get first guess of vertical velocities.

(*viii*) Invert $\nabla^2\chi = -\ \partial\omega/\partial p$ by relaxation to get χ.

(*ix*) Repeat above steps from (*vi*) to (*ix*).

The symbols used have their usual meanings. The meaning of other symbols used are given below :

H_L heating by latent heat of condensation.

H_S heating by sensible heat.

τ_x, τ_y frictional stresses along x and y axes

5. New operational NWP system

Recently a multivariate optimum interpolation objective analysis, and a regional primitive equation model have been installed on S-1000 at NIC computer, New Delhi. These models are now being checked and debugged for making them suitable for operational use. A global spectral model is also under adaptation and development in this connection. The details of models are given below :

5.1. *Multivariate optimum interpolation scheme*

The Optimum Interpolation (OI) scheme is a statistical technique for performing objective analysis of meteorological fields. The technique is based on the principle of applying corrections to the first guess at a grid point, the correction being calculated as a linear combination of the observed corrections at the observation locations surrounding the grid point.

The analysed value of a meteorological field '*F*' is expressed as :

$$F_g^a = F_g^g + \sum_{i=1}^{n} w_i f_i^\circ \qquad (5.1.1)$$

where, F_g^a = analysed value at the grid point

F_g^g = first guess value at the grid point

$\sum_{i=1}^{n} w_i f_i^\circ$ = weighted sum of the corrections (observation-first guess) at the n observation locations surrounding the grid point.

The weights w_i's are determined by minimising the analysis error through the least squares technique. The n observations are suitably selected from a three dimensional volume surrounding the grid point.

The matrix equation to be solved for the weights takes the form :

where ρ's represent the 'forecast error' or 'first guess error' correlation, η's the observational error correlations and ϵ's the ratio of observational error standard deviations to forecast error standard deviations.

The error correlations are modelled as a Gaussian function, and expressed as a product of horizontal and vertical correlation function. Horizontal correlation functions :

$$\mu_{ij} = \exp\,(-k_h\, S_{ij}^2)$$

vertical correlation function :

$$v_{ij} = \frac{1}{1+k_p\ \log_e^2\ (p_i/p_j)}$$

S_{ij} is the distance between location i and j, k_h and k_p are constants determining the shape of the correlation function.

The Eqn. (5.1.2) is solved by the method of conjugate gradients and weights w_i's determined. Grid point analysed values of the variables are determined with the help of Eqn. (5.1.1).

The main features of this analysis scheme are :

(*i*) The analysis is multivariate in h, u, v and univariate in q (specific humidity). The correlation functions for h (height) is modelled according to the above formulations. Those for the wind components u and v are expressed in terms of h-h correlations through a geostrophic coupling. This introduces an in-built mechanism for producing a balanced analysis. Only modest changes by way of non-linear normal mode initialization are needed.

(*ii*) OI is three dimensional and ensures more vertical consistency. The scheme facilitates use of single level data, allowing their influence to be distributed vertically.

(*iii*) OI provides a frame-work where data of varying type and quality can be accommodated.

5.2. *Spectral model for operational use*

The global spectral model based on the model of National Meteorological Centre, Washington is under development and adaptation for installation at New Delhi. The model has 40 wave rhomboidal truncation. It has 12 sigma layers in the veritcal.

The integration is preceded by a nonlinear normal mode initialization. The time integration is semi-implicit.

The following physical processes are incorporated in this model :

(*i*) Kuo's convection scheme,

(*ii*) Large scale condensation,

(*iii*) Boundary layer physics,

(*iv*) Hydrological cycle and

(*v*) Sensible heat transport from sea.

5.3. *Regional primitive equation model*

A semi-Lagrangian semi-implicit regional primitive equation model has recently been installed on S-1000 computer at National Informatics Centre, New Delhi. This model has been adapted and developed on the basis of the Florida State University Tropical Prediction Model (vector version). This model has been described by Bohra *et al.* (1986).

It is a ten-level model staggered in the vertical, with sigma coordinates. It covers area from 30°S to 50°N and 30°E to 150°E.

The basic formulation of the model is given by :

(i) *Momentum equations*

$$\frac{Du}{Dt} = -\dot{\sigma}\frac{\partial u}{\partial \sigma} + v(f + \frac{u}{a}\tan\phi) - g\frac{\partial z}{\partial x} - RT\frac{\partial}{\partial x}\ln p_s + F_x \qquad (5.3.1)$$

$$\frac{Dv}{Dt} = -\dot{\sigma}\frac{\partial v}{\partial \sigma} - u\left(f + \frac{u}{a}\tan\phi\right) - g\frac{\partial z}{\partial y} - RT\frac{\partial}{\partial y}\ln p_s + F_y \qquad (5.3.2)$$

(ii) *Thermodynamic equations*

$$\frac{DT}{Dt} = -\dot{\sigma}\frac{\partial T}{\partial \sigma} + kT\left(\frac{\dot{\sigma}}{\sigma} + \frac{D}{Dt}\ln p_s\right) + \frac{H + F_\theta}{c_p} \qquad (5.3.3)$$

(iii) *Continuity equation*

$$\frac{D}{Dt}\ln p_s = -\frac{\partial \dot{\sigma}}{\partial \sigma} - \nabla . \mathbf{V} \qquad (5.3.4)$$

(iv) *Moisture continuity equation*

$$\frac{Dq}{Dt} = -\dot{\sigma}\frac{\partial q}{\partial \sigma} + e - r + F_q \qquad (5.3.5)$$

(v) *Hydrostatic equation*

$$\frac{\partial z}{\partial \sigma} = -\frac{RT}{g\,\sigma} = -\frac{c_p\,\theta}{g}\frac{\partial \pi^k}{\partial \sigma} \qquad (5.3.6)$$

(vi) *Equation of state*

$$\alpha = \frac{RT}{p} = RT/\sigma p_s \qquad (5.3.7)$$

(vii) *Poisson's equation*

$$\frac{T}{\theta} = \left(\frac{p}{1000}\right)^k = \pi^k \qquad (5.3.8)$$

(viii) *Surface pressure tendency equation*

$$\frac{\partial p_s}{\partial t} = -\int_{\sigma T}^{1} \nabla . (p_s . \mathbf{V})\, d\sigma \qquad (5.3.9)$$

(ix) *Vertical velocity equation*

$$\frac{\partial \dot{\sigma}}{\partial \sigma} = \left(\widetilde{\mathbf{V}} - \mathbf{V}\right) \cdot \nabla \ln p_s + \nabla . \left(\widetilde{\mathbf{V}} - \mathbf{V}\right) \qquad (5.3.10)$$

where,

$$\widetilde{\mathbf{V}} = \frac{1}{(1-\sigma_T)}\int_{\sigma_T}^{1} \mathbf{V}\, d\sigma$$

The semi-Lagrangian formulation defined along the trajectory gives :

$$\frac{D_H F}{Dt} = \frac{F^+ - F^\circ}{\triangle t} \qquad (5.3.11)$$

and the average value of the forcing for the semi-implicit time integration is defined for linear terms:

$$\bar{F} = (F^+ + F^\circ)/2 \qquad (5.3.12)$$

and for non-linear terms:

$$\{F\} = (F^{\circ} + 2F - F^{-})/2 \qquad (5.3.13)$$

where F is the value of the variable at any point x, y, σ at time 't'; $F+$ is its value at point x, y, σ and $t+\triangle t$; F^{-} is its value at point x, y, σ and $t-\triangle t$, and F° is its value at point $x-\zeta, y-\eta, \sigma, t$.

With these notations the model equations change to :

$$\frac{D_H u}{Dt} + \frac{\partial \overline{P}}{\partial x} = \left\{ S_1 \right\} \qquad (5.3.14)$$

$$\frac{D_H v}{Dt} + \frac{\partial \overline{P}}{\partial y} = \left\{ S_2 \right\} \qquad (5.3.15)$$

$$\frac{D_H}{Dt}\left[\frac{1}{\gamma^*}\frac{\partial P}{\partial \sigma} + \sigma \ln p_s\right] + \overline{\dot{\sigma}} = \left\{ S_3 \right\} \qquad (5.3.16)$$

$$\frac{D_H q}{Dt} = \left\{ S_4 \right\} \qquad (5.3.17)$$

$$\frac{D_H}{Dt} \ln p_s + \overline{\nabla . \mathbf{V}} + \frac{\partial \dot{\sigma}}{\partial \sigma} = 0 \qquad (5.3.18)$$

The trajectory calculations for finding the initial guess position of point 'o' is done by :

$$s = u.t + \tfrac{1}{2}\, \alpha . t^2$$

where α is the acceleration. Several iteratively improved estimates are obtained for α and point 'o'.

The interpolation of variables at point 'o' is made by a fourth order correct scheme.

A Helmholtz equation in P is obtained by algebraic manipulations of Eqns. (5.3.14) to (5.3.18), which is first of all solved to obtain 'P'. Once the values of P are known the Eqns. (5.3.14) to (5.3.18) are solved along the trajectories to get forecast values of variables.

The symbols used in this section have the usual meaning. The meaning of the other symbols are :

a	Radius of the earth
e	Evaporation
F_x, F_y	Horizontal diffusion of momentum
F_θ, F_q	Horizontal diffusion of heat and moistures
H	Diabatic heating
P	$=g.z + RT^* \ln(p_s)$
p_s	Surface pressure
r	Precipitation
S_1	Non-linear terms of the zonal momentum equation
S_2	Non-linear terms of the meridional momentum equation
S_3	Non-linear terms of the thermodynamic equation
S_4	Non-linear terms of the continuity equation of moisture
k	$= R/c_p$
ϕ	Latitude

$$v = \frac{R}{\sigma}\left[\frac{kT}{\sigma} - \frac{\partial T}{\partial \sigma}\right]$$

$$F^* = \frac{\iint F \cos\phi \, d\lambda \, d\phi}{\iint \cos\phi \, d\lambda \, d\phi}$$

A dynamic normal mode initialization scheme is used in this model. During initialization the integration is done with one step forward and one step backward with the following scheme :

$$\overset{*}{u}_{n+1} = u_n + \triangle t \left(\frac{\partial u}{\partial t}\right)_n \quad \text{(forward step)}$$

$$\overset{**}{u}_n = \overset{*}{u}_{n+1} - \triangle t \left(\frac{\partial u}{\partial t}\right)^*_{n+1} \quad \text{(backward step)}$$

$$\bar{u}_n = 3u_n - 2\overset{**}{u}_n$$

For every twenty time-steps the linear terms are allowed to vary but nonlinear terms including physics are kept constant. Such five cycles are performed. This is equivalent to normal mode initialization.

The parameterization of the following physical processes is included in the model :

(*i*) Dry convective adjustments,

(*ii*) Shallow convection,

(*iii*) Deep convection,

(*iv*) Large scale non-convective precipitation,

(*v*) Radiation with clouds estimated from model variables,

(*vi*) Planetary boundary layer physics and

(*vii*) Energy balance at the earth surface.

Dry convective adjustment

The dry convective adjustments made by changing the temperatures of the unstable layer by keeping the total dry static energy 'E' constant, where,

$$E = \int_{p_1}^{p_2} \left(gz + c_p T \right) dp$$

Shallow convection

In the area of conditionally unstable atmosphere with relative humidity of less than 80% where the processes remain non-precipitating, the diffusion of moisture and heat are suitably parameterized.

Deep cumulus convection

In deep cumulus convection the supply of moisture is

$$I_L = -\frac{1}{g}\int_{p_T}^{p_B} \omega \frac{\partial q}{\partial p}\, dp$$

which is augumented by meso-scale systems to give

$$I = I_L(1 + \eta)$$

The total moisture required to produce overcast grid area is :

$$Q = \frac{1}{g}\int_{p_T}^{p_B} \frac{(q_s - q)}{\triangle\tau}\, dp + \int_{p_T}^{p_B}\left[\frac{c_p T(\theta_s - \theta)}{L\theta\triangle\tau} + \frac{\omega c_p T}{L\theta}\frac{\partial\theta}{\partial p}\right] dp$$

$$\equiv Q_q + Q_\theta$$

The partitioning of moisture supply for heating and moistening is determined from vertical velocity and vorticity values, based on regression coefficients obtained from GATE results, which give fractional cloud areas; for heating and moistening :

$$a_\theta = I_L\,(1+\eta)\,(1-b)/Q_\theta$$

$$a_q = I_L\,(1+\eta)\,b/Q_q$$

The precipitation from deep convection will, therefore, be :

$$R_c = \frac{a_\theta\,\pi}{Lg}\int_{p_T}^{p_B}\left[\frac{c_p\,(\theta_s - \theta)}{\triangle\tau} + \frac{\omega\, c_p}{\theta}\frac{\partial\theta}{\partial p}\right] dp$$

Large scale precipitation

If the atmosphere is absolutely stable and the humidity exceeds 80% and the vertical motion is upwards the large scale precipitation heating is given by :

$$H_L = \left[\frac{c_p\,T}{\theta\, Lq_s} + \frac{\epsilon L}{RT\theta}\right]^{-1} \times$$

$$\left[-\omega\left(\frac{\partial\theta}{\partial p} - \frac{RT\theta}{\epsilon L q_s}\frac{\partial q_s}{\partial p}\right)\frac{\epsilon L}{RT\theta} + \text{other small terms}\right]$$

Radiation

In this model the radiation processes in the atmosphere are divided into three components :

(*i*) Absorption of the short wave solar radiation,

(*ii*) Cooling due to long wave radiation and

(*iii*) Sensible heat balance at the earth surface.

The absorption of radiation in the atmosphere by moisture only has been considered. The emissivity method has been used for calculating long wave radiation transfers. For this process the cloud types amounts and heights are estimated from the predicted humidity conditions.

Diurnal and seasonal variation of short wave radiation have been taken into account. The solar zenith angle ξ at any place and time is given as :

$$\cos\xi = \sin\phi\,\sin\delta + \cos\phi\,\cos\delta\,\cos\alpha$$

where δ is the declination of sun and α is the hour angle. The optical water vapour depth from the top of the atmosphere is given by :

$$w\,(p) = \frac{1}{g}\int_{p_T}^{p_i} q\left(\frac{p}{p_0}\right)\sqrt{\frac{T_0}{T}}\; dp + w_T$$

The short wave solar radiation S_0 is partly scattered and partly absorbed by the atmosphere. The part reaching the ground is reflected as diffuse radiation. The net downward flux of this absorbed radiation at any level '*i*' is :

$$S_i^a = S^a\,[1 - A(w_i \sec\xi)] - S^a[1 - A(w_0 \sec\xi)]\,\alpha_s \cdot [1 - A\{1.66\,(w_0 - w_i)\}]$$

It will get modified if there are clouds above or below the level.

The long wave radiation flux reaching any level '*i*' in the presence of clouds above and below the levels are given as :

$$\overset{\downarrow}{F_i} = \sigma\, T_{cB}^{4}\left[1 - \epsilon(w_i - w_{cB})\right] - \int_{w_{cB}}^{w_t} \sigma\, T^4 \frac{\partial}{\partial w}\,(w_i - w)\, dw$$

$$\overset{\uparrow}{F_i} = \sigma\, T_{cT}^{4}\left[1 - \epsilon(w_{cT} - w_i)\right] - \int_{w_i}^{w_{cT}} \sigma T^4 \frac{\partial\epsilon}{\partial w}\,(w - w_i)\, dw$$

These are modified if there are no clouds. Knowing the upward and downward flux of radiation the net temperature changes for any layer is given as :

$$\frac{\partial T}{\partial t} = \frac{g}{c_p}\left[\frac{\partial F}{\partial p} + \frac{\partial S^a}{\partial p}\right]$$

Surface energy balance

The surface energy balance is made with the following enquation :

$$SE = \overset{\downarrow}{F_L} - \sigma T_g^4 + \overset{\downarrow}{F_s} - \alpha\,\overset{\downarrow}{F_s} + \rho c_p\, c_D\,|\,\mathbf{V}_0\,|\,(T_g - T_s) + \rho c_q\, L\,|\,\mathbf{V}_0\,|\,(q_g - q_s)$$

This equation gives the surface temperature on solution.

Planetary boundary layer

A very sophisticated boundary layer parameterization is used in this model. It uses similarity analysis approach for the specification of surface fluxes.

6. Future outlook

The future requirements of weather forescast to meet the needs of agriculture, industry, transportation and energy and water management projects cannot be tackled adequately by existing synoptic methods of weather prediction. No synoptic method exists to prepare medium range forecasts of 5-10 days duration which are of great importance for agricultural planning. The experience of other NWP centres like ECMWF has shown that the numerical weather prediction can produce useful forecasts of about a week's duration in middle latitudes. It is, therefore, necessary that the numerical methods are used for the analysis and prediction to provide support for existing synoptic methods. Great emphasis is, therefore, being given to NWP research in India Meteorological Department. However, due to some practical difficulties the pace of progress is rather slow. The main difficulty is lack of adequate computing facilities. Efforts are in progress to overcome them to the extent possible.

It is hoped that soon suitable limited area and global models will be put in use for operational weather prediction.

In the next few years, India Meteorological Department hopes to develop an operational NWP system consisting of :

— A global data reception and monitoring system,

— A suitable data assimilation system to incorporate non-conventional data from satellites, aircraft and other sources into routine meteorological data sets,

— A global data anlysis system for various fields, like geopotential height, surface pressure, wind and humidity, etc,

— A suitable high resolution limited area model to prepare short range forecast of 1 to 3 days duration,

— A suitable global spectral model to prepare medium range forecast guidance of 5 to 7 days duration and

— A suitable system for interpretation of model output results.

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