SESSION VI

THEORETICAL AND EXPERIMENTAL STUDIES

CHAIRMAN : PROF. T. N. KRISHNAMURTI

Florida State University, U.S.A.

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The mid-tropospheric cyclone : Numerical experimentation

FREDERICK H. CARR

Department of Atmospheric Science, State University of New York,
Albany, New York

ABSTRACT. The mid-tropospheric cyclone over the west coast of India has been recognized as playing a major role in producing monsoon rainfall over that region. In this study a real data set is constructed for 1 July 1963 (12 GMT). This initial state represents an early stage in the mid-tropospheric cyclone that was extensively documented by Miller and Keshavamurthy (1968). An *x-y-p* semi-Lagrangian primitive equation model developed at Florida State University is applied to this data set to make several short-range forecasts. The observed structure of the incipient disturbance indicates that it exists in a favourable dynamic and thermodynamic environment for development. The forecasts are qualitatively successful, with good rainfall distribution, but the precipitation amounts are too small. In order to develop the kinematic and thermal fields that are quantitatively consistent with the true latent heating rates, a heating function was derived from the observed rainfall totals. The resulting experiments led to more realistic forecasts, as the mid-tropospheric cyclone intensified as observed. The results of extensive vorticity and energy budget analysis support the hypothesis that the MTC is intensified and maintained by a modified CISK process, in which a cooperative feedback between large-scale convergence and convective latent heat release exists without the benefit of a cyclonic Ekman layer.

1. Introduction

One of the most interesting features that has been observed during the summer monsoon season over southern Asia is the mid-tropospheric cyclone that occasionally exists over the northeastern Arabian Sea. In the most comprehensive observational study to date, Miller and Keshavamurthy (1968) found that during July 1973 a mid-tropospheric cyclone (hereafter denoted by MTC) formed *in situ* near the west coast of India remained quasi-stationary for nearly two weeks, had its maximum intensity at 600 mb with no organized circulation at the surface or above 300 mb and caused heavy, beneficial rains over much of western India during its lifetime. In this study, a real data set is constructed from the above case study in order to study the dynamics and predictability of the MTC with a numerical model. The data chosen is 1 July 1963, 12 GMT, which represents an early stage in the life cycle of the Miller and Keshavamurthy cyclone.

2. The model

A quantitatively accurate model of the MTC should include the effect of many environmental influences. Among these are the effects of the orography to the east and north, the heat lows to the north and northwest, the steady, moist southwesterly flow in the lower troposphere, the upper tropospheric easterly jet, the mean monsoon trough and its modifications by monsoon depressions and planetary waves, the varying static stability over the region, differential radiative heating and the presence of simultaneous stable and convective heating. Since only a fairly comprehensive primitive equation model can hope to include all these features, it was chosen as the primary tool for this study. The model utilized is the *x-y-p*, semi Lagrangian primitive equation model that has been developed and used by Dr. Krishnamurti and his colleagues at Florida State University over the past decade (Krishnamurti *et al.* 1976).

The horizontal resolution used is 2° latitude and longitude (coarse mesh) and also 1° (fine mesh). The model has five layers in the vertical, with $\omega=0$ at 100 mb as the top boundary condition. The lower boundary condition of $\omega=0$ except near topography gives rise to a tendency equation for z_0, the 1000 mb height surface. The east-west lateral boundary conditions are cyclic, while rigid, slippery walls are imposed to the north and south. The main physical processes included in the model are surface friction, horizontal and vertical diffusion and the diabatic heating effects of large-scale condensation (stable heating), convective heating [*via* an improved version of the Kuo (1965) scheme], short and long wave radiative heating and sensible and latent heat flux from the surface. For more details on the numerical and physical aspects of the model used here, (Carr *see* 1977).

3. Analysis and observed structure

The wind, temperature and relative humidity fields at the standard levels were subjectively analyzed, along with surface pressure. From these fields, the five prognostic variables u, v, $\dot{\theta}$, q and z_0 were obtained at the model levels. The divergence correction procedure as described by Washington and Baumhefner (1975) was applied. A dynamic or iterative initialization period of 18 hours preceded each prediction in order to allow small scale gravity waves and the external wave to disperse or dissipate. Since much of the analysis was over data poor regions, large-scale imbalances can occur between the wind and temperature fields which are not corrected by the dynamic initialization. This gives rise to internal gravity-inertial waves during the early stages of each forecast. These waves, a recurrent problem in tropical numerical weather prediction, dissipate over a 12-18 hour period and subsequently do not significantly affect the forecasts.

Fig. 1 is an example of the many initial state diagrams available. In Fig. 1 (a), the 600-mb wind field shows two cyclonic centres, the MTC over the west coast of India and a monsoon depression off the east coast. The 600-mb vorticity field (Fig. 1b) indicates that the monsoon depression is initially more intense than the MTC. Subsequently, the monsoon depression became weaker while the MTC intensified, a sequence that was correctly predicted by the model.

The vertical kinematic structure across the domain along 18°N is shown in Fig. 2. The maximum amplitude in the v-component (Fig. 2a) of 4 ms^{-1} is found at 600 mb. The relative vorticity maximum (Fig. 2b) is also at 600 mb, with values near zero at the surface and negative above 300 mb. The differences between MTC and monsoon depression structure are clearly shown in Fig. 2 (b), the latter having a vorticity maximum near 700 mb which extends to the surface. The initial vertical motion field (Fig. 2c) has two upward motion maxima; one near 900 mb which is induced by the Western Ghats and a second one at 500 mb. The horizontal and vertical scales of the MTC as deduced from this and other figures not shown are 1500 km and 8 km respectively.

The vertical thermodynamic structure of the MTC along the same x-p cross-section is displayed in Fig. 3. The top panel depicts the varying dry static stability across the region. The temperature anomaly cross-section (Fig. 3b) shows that both the MTC and monsoon depression are cold core in the lower troposphere, with a large scale warm anomaly aloft. Due to the presence of the hot Arabian desert, the cold anomalies are exaggerated; an amplitude of 1°-2° C is more realistic. Fig. 3(c) presents the vertical structure of moist static energy ($E_S = gz + c_p T + Lq$), a quantity which is proportional to equivalent potential temperature. It shows two important features : (*i*) that the MTC exists above a maximum of high energy boundary layer air and (*ii*) that the convective instability (determined by the vertical gradient of E_S) is largest within the MTC. This indicates that this region is highly conducive for the development of deep convection. Both Figs. 2 and 3 demonstrate that this incipient MTC exists in a favourable dynamic and thermodynamic environment for development.

4. Forecast results

Many forecast experiments were performed, although only a few will be discussed here. Since the wind, temperature, moisture and other large-scale fields were generally forecast well, the discussion will first concentrate on rainfall prediction. The location of the precipitation maxima were reasonable but the amounts were underestimated. An example of a north-south cross-section of predicted latent heating rates along the west coast of India (74°E) is shown in Fig. 4. Convective heating (Fig. 4c) is spread along the coast but has maximum of 6°C per day at 300 mb near 19° N, an area where deep cumulonimbus clouds were observed. Maximum stable heating (Fig. 4b) is at 500 mb and is confined near the centre of the storm (where the maximum rising motion exists). The presence of large-scale condensation is important since the total latent heating profile (Fig. 4a) has its maximum near 500 mb of 12°C per day.

Despite the qualitative success of the forcasts, if the rainfall rates are not correct, then a quantitative

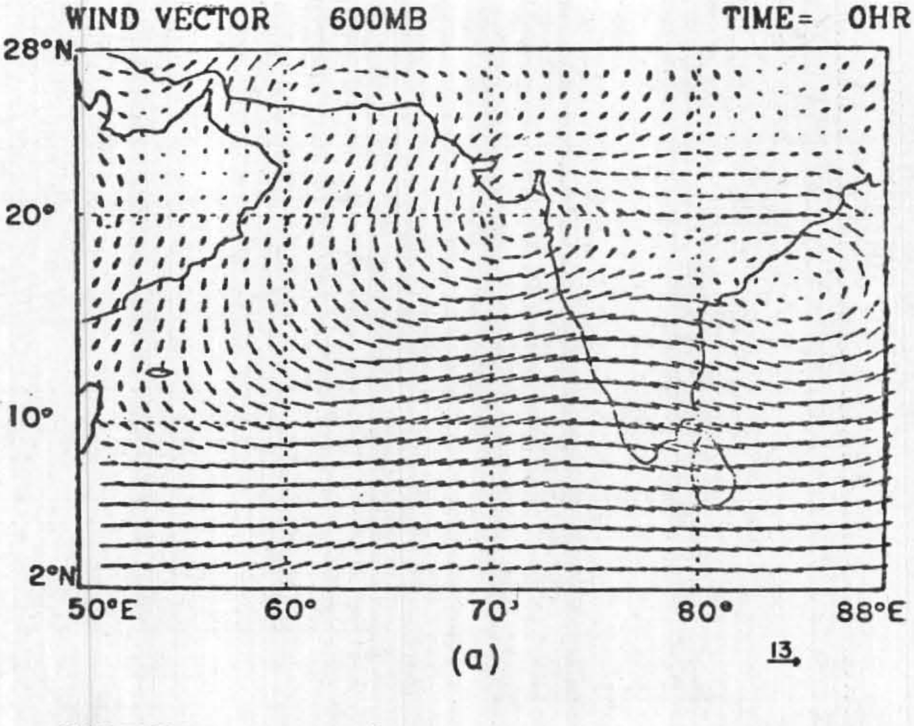

Fig. 1 (a). Initial 600 mb wind vector field (ms^{-1})

(b). Initial 600 mb vorticity field ($\times 10^{-7} s^{-1}$)

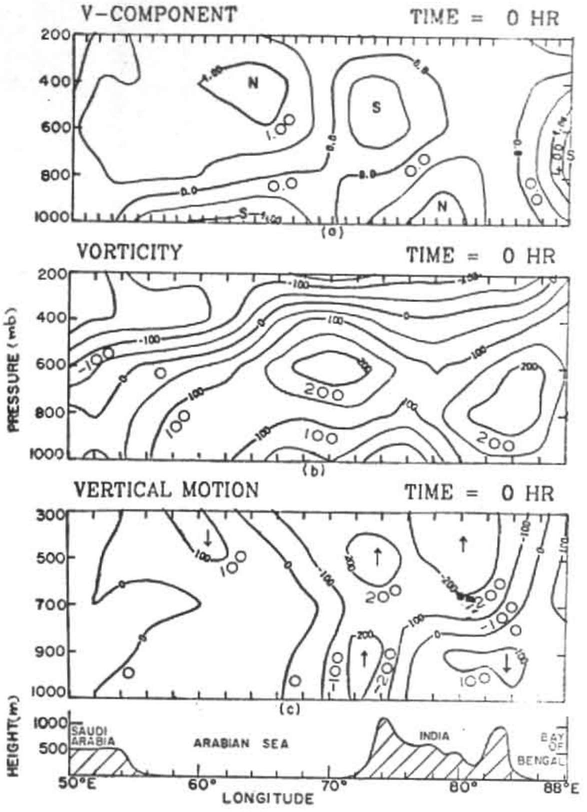

Fig. 2. East-west vertical cross-section along 18°N at the initial time : (a) v-component (ms^{-1}); (b) vorticity ($\times 10^{-7}$ s^{-1}) and (c) vertical velocity ($\times 10^{-5}$ mb s^{-1})

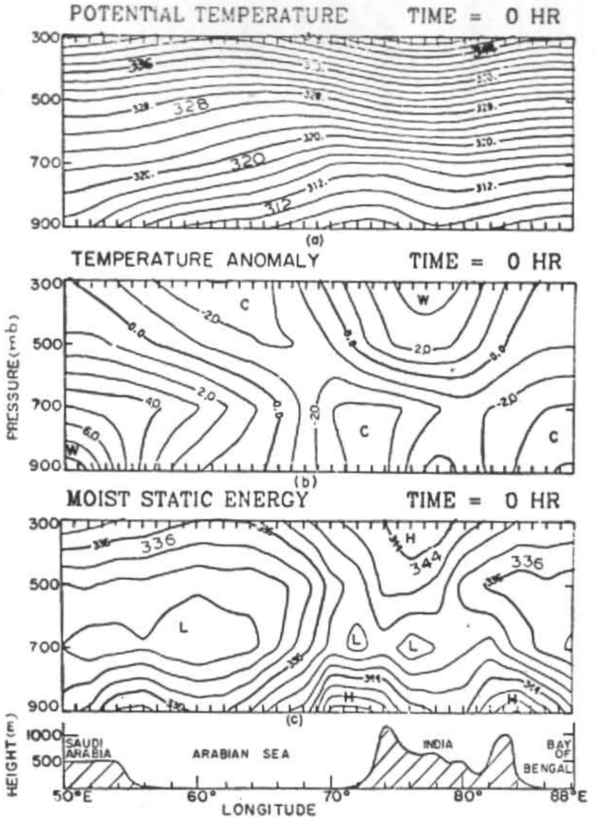

Fig. 3. East-west vertical cross-section along 18°N at the initial time : (a) potential temperature (°C); (b) temperature anomaly (°C) and (c) moist static energy ($\times 10^{3}$ m^{2} s^{-2}).

analysis of the forecasts would not be representative of the observed MTC. Here, the predicted rainfall rates were too low, primarily because the convective parameterization scheme used could not account for all the mesoscale and cloud-scale moisture convergence that must occur in active convective systems. In order to develop motion and thermal fields which are internally consistent with the true precipitation rates, the observed rainfall amounts were used to derive an analytical expression for the latent heating term at each grid point. Based on the earlier results shown in Fig. 4, a parabolic vertical heating distribution was assumed. Aside from the specified latent heating, the model remains the same, with the observed July 1 data specifying the initial conditions.

In Fig. 5, the results of a 72-hour coarse mesh integration is shown. The circulation organizes as observed over the west coast of India while the vorticity maximum is nearly twice that predicted in the earlier experiments. Although the vorticity centre has the correct horizontal scale, the circulation as shown by the wind vector in Fig. 5(a) is too large, a common problem with coarse mesh, limited area models. Fig. 6(a) also shows the 72-hour vorticity prediction in the y-p cross-section format. The MTC has nearly extended to the surface but not above 300 mb; the maximum is maintained at 600 mb. This distribution can be explained using the two lower panels. The divergence pattern in Fig. 6(b) indicates that vorticity generating convergence has a maximum at 800 mb beneath the MTC centre while divergence exists at 200 mb. The vertical motion field (Fig. 6c) has a rising centre throughout the MTC, with a maximum at 500 mb, hence advecting lower level vorticity into the mid-troposphere.

Fine mesh forecasts were made (not shown) and displayed quantitative improvemets over the coarse mesh forecasts. The MTC intensified more realistically and the rising motion became 5×10^{-3} mb s^{-1}. Moisture is supplied to the MTC, *via*

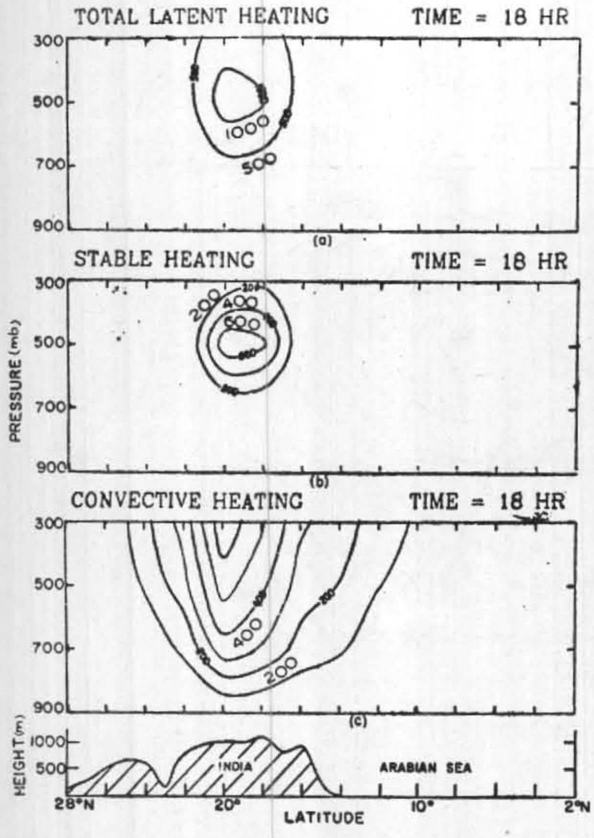

Fig. 4. North-south vertical cross-section along 74°E of the predicted latent heating rates at 18 hours ($\times 10^{-7}$ °C s^{-1}) : (a) total latent heating rate, (b) stable heating rate and (c) convective heating rate

the large-scale convergence in the lower troposphere and by orographic uplift of the moist boundary layer air. An experiment in which no latent heating at all was allowed resulted in a MTC which rapidly dissipated and moved westward.

5. Dynamical analysis and summary

As suggested by Fig. 6, a vorticity budget analysis showed that the vorticity maximum at 600 mb was maintained by horizontal convergence and vertical advection of vorticity. This vertical motion and convergence are, in turn, due to the large amount of latent heat release implied by the observed rainfall totals. In order to examine the mechanisms responsible for the quasi-stationary character of the MTC, the vorticity budget was performed separately over the eastern and western domains of the storm. It was found that horizontal vorticity advection as well as the beta term predict a westward movement of the MTC. In addition, the warm advection present over the Arabian Sea indicates that quasi-geostrophic as well as barotropic dynamics would induce a westward translation. To offset these influences, a large convergence production of vorticity exists over the west coast of India. Since part of this convergence is due to the mountains, the MTC may be said to be quasi-stationary due partly to topographic anchoring and partly to the dry, subsiding air over the western Arabian Sea. Hence the MTC position may be the net result of a continuous cyclogenesis due to CISK near the Indian coast and continuous cyclolysis over the central Arabian Sea as the dynamical tendency for the storm to move westwards is negated by the quenching of convection in the dry air.

The energy cycle over the forecast domain determined from the experiments is as follows : latent heating and differential radiative cooling create both zonal and eddy available potential energy (APE); the zonal APE goes primarily into zonal kinetic energy with a small portion increasing eddy APE; eddy kinetic energy is generated almost totally by eddy APE, the barotropic zonal to eddy kinetic energy exchanges being weak or reversed; most of the eddy APE is created by latent heating, and, of that, about 50-75% is from convective heating. In addition, the (ω' T') structure of the MTC as seen in Figs. 2 and 3 indicates that eddy kinetic energy is destroyed in the lower troposphere while being created in the mid and upper troposphere; this helps explain the lack of circulation near the surface. A large conversion of eddy to zonal kinetic energy occurs at 200 mb which helps sustain the easterly flow above the MTC.

In summary, the results of all the experiments clearly suggest that a modified CISK process, in which a cooperative feedback between the large-scale moisture convergence and the latent heat release by convective (and non-convective) clouds exists without the benefit of a cyclonic Ekman layer, is the primary mechanism which intensifies and maintains the mid-tropospheric cyclone. Much more observational data is needed, though, in order to obtain a more complete description of the "average" MTC. Due to the quasi-equilibrium that exists between the large-scale MTC flow and its ensemble of convective elements, its large rainfall rates and its quasi-stationarity, long lifetime and proximity to land, future observational studies of the MTC may yield valuable knowledge on the

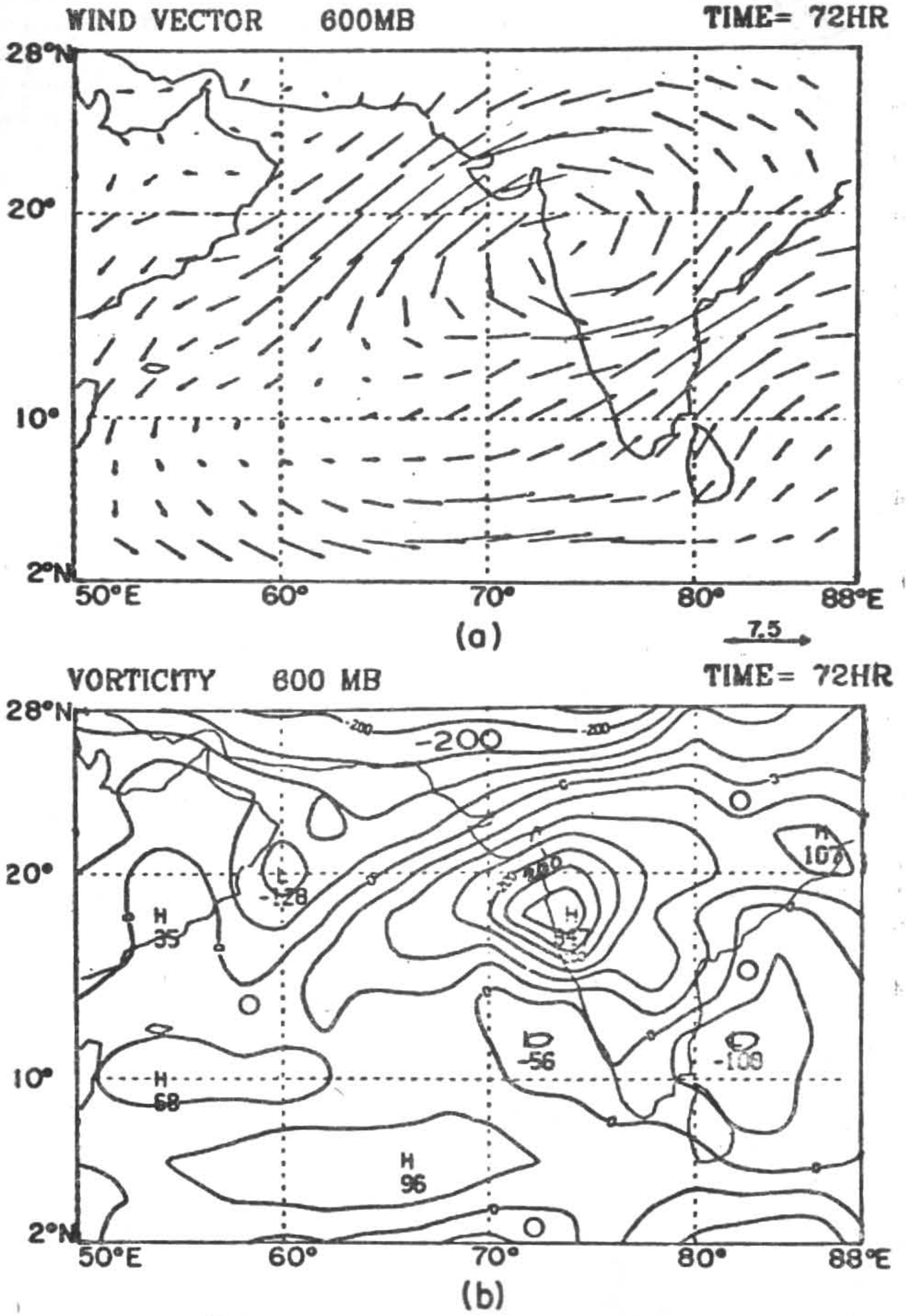

Fig. 5. 600 mb wind field at 72 hours : (a) wind vectors (m s^{-1}) and (b) vorticity ($\times 10^{-7}$ s^{-1})

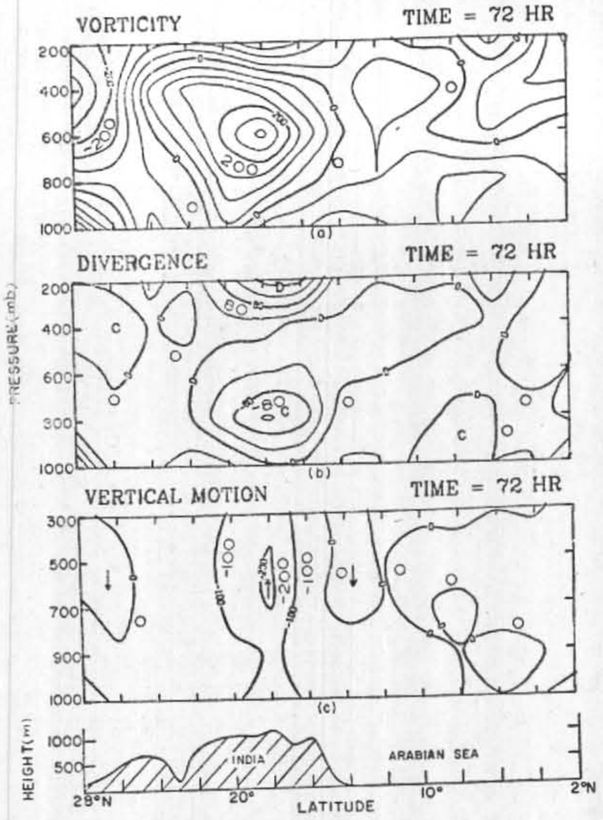

Fig. 6. North-south vertical cross-section along 74°E at 72 hours : (a) vorticity ($\times 10^{-7}$ s^{-1}), (b) divergence ($\times 10^{-7}$ s^{-1}) and (c) vertical velocity ($\times 10^{-5}$ mb s^{-1})

important scale interaction and cumulus parameterization problems.

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