A model study of the growth of summer monsoon disturbances

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Using an appropriate north-south distribution of a diabatic heating in a global multilevel spectral model, we have generated summer monsoon type of basic flow. Then we superimposed a pulse at the point of inflexion to the north of the jet at 900 mb. Using conditional instability of the second kind (CISK) type of cumulus heating we integrated the model keeping the basic flow fixed. We found that the pulse grows into observed type of monsoon depression. When cumulus heating was absent the pulse did not show any appreciable growth. The detailed computations of energetics show that the main growth mechanism of the pulse is by baroclinic energy exchange in the presence of cumulus heating.

Monsoon disturbances which form over north Bay of Bengal and move westnorth-westwards across central and adjoining north India are the main rain-producing systems during the summer monsoon season. There have been many studies about the mechanisms of formation and the structure of these disturbances. The studies for understanding the mechanisms of formation fall into mainly two categories: (i) Instability studies of the monsoon flow with horizontal and vertical shears and with the inclusion of cumulus heating and (ii) Numerical model studies where the growth of monsoon depressions is predicted from the observed data and calculations of energy conversion are done. The consensus of most of these studies is that monsoon disturbances grow as a result of combined barotropic-baroclinic instability of monsoon flow in the presence of cumulus heating. There have also been calculations showing that cumulus heating destabilizes baroclinic modes. In numerical models calculations of energy conversions yield large values for $A_e$ to $K_e$ (eddy available potential energy to eddy kinetic energy) in the presence of monsoon heating. Conversion of $K_e$ to $K_d$ (zonal kinetic energy to eddy kinetic energy) is small contrary to suggestions of some linear studies.

We feel that there is a strong need for a third kind of studies where the nonlinear evolution of monsoon perturbations is studied using idealized basic flows with cumulus heating and for doing detailed calculations of energetics. Such studies can clarify many of the dichotomies which exist between linear studies and nonlinear numerical model studies with real data.

In the present study we generated a monsoon zonal flow which has both meridional and vertical shear by imposing an appropriate heating distribution in a global spectral model. Then a weak pulse perturbation was superposed on the basic flow at the point of inflexion and cumulus heating was switched on. The nonlinear evolution of the growing perturbation was studied.

Model study

We have used an atmospheric model based on the primitive equations. It is a global spectral model (in $\sigma$ coordinates) with five levels in the vertical and rhomboidal truncation at 35 waves corresponding to a horizontal resolution of 2° latitude by 2.8° longitude. The model formulation has been described in Keshavamurty et al. It has $\nabla^2$ type diffusion and linear drag of five days. It has no topography. In the model, an appropriate south to north zonally symmetric diabatic heating distribution $\bar{q}(y,\sigma)$ is imposed. The model is then run up to 25 days till a steady state is reached. The heating profile $\bar{q}(y,\sigma)$ is adjusted such that fairly realistic zonal winds are generated. The idealized basic monsoon flow thus generated is shown in Figure 1(a, b), with $U$ profiles at 900 mb (maximum westerly of 10 m sec$^{-1}$) and 100 mb (maximum easterly 27 m sec$^{-1}$). Figure 2 shows the meridional profile of gradient of potential vorticity (quasi-geostrophic) at 900 mb of the generated basic flow. It is seen that this changes sign near 21°N. This indicates the possibility of combined barotropic-baroclinic instability.

Next a small pulse perturbation $\psi$ is superposed at 900 mb (21°N, 90°E) (Figure 3a). It is a pulse with a half width of 4° in latitude and 5.6° in longitude having magnitude of zonal wind 0.5 mps (Figure 3b).

$$\psi(x,y) = A e^{-\left(\frac{\left|\alpha \right|^2}{a^2} \right)} e^{-\left(\frac{\left|\beta \right|^2}{b^2} \right)}, \tag{1}$$

where $\alpha = 1.7$, $\beta = 2.4$, $\epsilon = 0.5$, $\gamma = 21$ N, $\lambda = 90$ E, $A = 2.25 \times 10^{-5}$.

The amplitude of the pulse falls to half its central value at the nearest neighbouring grid points. It is superposed at the inflexion point in the low level basic
Figure 1. Model simulated zonal wind ($U$) profile at 900 mb (a) and 100 mb (b) in m/s.

Figure 2. Meridional profile of gradient of potential vorticity of the basic flow at 900 mb (m$^{-1}$s$^{-1}$).

Flow at 21° N latitude, i.e. to the north of the low level jet. Next cumulus heating $\tilde{Q}$ is switched on. For $\tilde{Q}$ we have used the simplified cumulus conditional instability of the second kind (CSIK) heating scheme of Charney and Eliassen$^{17},$

where

$$\frac{\tilde{Q}}{C_p} = H_f(p) \frac{p}{R} s \left[ \rho g \frac{K_c}{2/\theta} \sin (2\pi) \zeta_{900} \right] \times 0.5 \times \pi \times \sin (\pi \sigma)$$

where $H_f(p) = 1.5,$ and the various symbols have the following meanings: $R$ is the gas constant, $s$ the static stability, $\rho$ the density of air, $K_c$ the eddy viscosity coefficient, $\sigma$ the surface cross-isobaric angle, and $\zeta_{900}$ represents vorticity at 900 mb due to pulse.

The vertical profile of the cumulus heating used here is based on the study of Mohanty and Das$^{18}.$ It has a maximum of cumulus heating at 500 mb. Therefore a vertical distribution of the form $\sin (\pi \sigma)$ was used. The model equations are integrated for five days keeping the basic flow fixed, to study the time evolution of the pulse.

Figure 3. Pulse in $\psi$ (m$^2$s$^{-1}$) (three-dimensional view) at 900 mb (21° N, 90° E) (a), pulse (vortex) at 900 mb having maximum amplitude of wind 0.5 m/s$^{-1}$ (b).
Results and discussion

Characteristics of the growing disturbance

Figures 4a–e show the total wind field for the first five days (in the case of the incipient vortex superimposed to the north of the low level jet). It is clearly seen from the figures that cyclonic flow around the centre of the perturbation has steadily grown in strength from day 1 to day 5. The vortex is strongest in the lower troposphere. The maximum amplitude of the perturbation wind increased to 1.2, 1.4, 1.6, 1.8 and 2.0 m/s on the first, second, third fourth and fifth day respectively. Figure 5 shows the perturbation wind field on the fifth day. It is clear that the perturbation has grown into depression strength (20 m/s) on the fifth day and its scale is around 2000 km.

Figures 6a–d show the east-west section through the

Figure 4. Total wind field at 900 mb on day 1, 2, 3, 4, 5 (a, b, c, d, e) having maximum amplitude of wind 123, 119, 113, 114 and 245 m/s respectively.
Another feature to be noticed is the anticyclonic vorticity on either side of the main vortex, especially to the east of the main cyclonic vortex. All these aspects are in fair agreement with the observed features of monsoon depressions.

A second calculation was done by imposing the pulse at 21°N and the model was integrated for five days without CISK heating. No growth of the pulse was noticed in this case. This shows that only horizontal and vertical shear are not sufficient for the growth of the perturbation but cumulus heating is essential for the growth of the disturbance.

**Vertical circulation and energetics**

Figures 7a–e show east-west sections of vertical motion through the centre of the depression on the first, second, third, fourth and fifth days. The upward motion at the centre and descending motion on either side is clearly seen. The steady growth of the vertical circulation with time is clearly brought out. A comparison of Figure 6d with 7d brings out that there

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**Figure 5.** Perturbation wind field at 900 mb on day 5 having maximum amplitude of wind 20 m/s.

**Figure 6.** East-west section (x-p plot) of meridional wind (a), vorticity (b), divergence (c), temperature (d) through the centre of the vortex.
is rising of warm air and sinking of cold air. This results in baroclinic energy conversions and hence growth of the disturbance. In order to see how this simulated depression is maintained we have carried out detailed energetics calculations over the (limited) area surrounding the position of the pulse, i.e. from 1° N to 41° N and 70.3° E to 112.5° E. The expression for different forms of energy can be written as follows (see, for instance Rajamani and Sikdar):

$$A_{\ell} = \frac{C_p}{2} \int_{m} \gamma (T - \bar{T})^2 \, dM,$$

$$A_e = \frac{C_p}{2} \int_{m} \gamma (T^2) \, dM$$
\[ K_Z = \frac{1}{2} \int_M (\{u\}^2 + \{r\}^2) \, dM, \]
\[ K_L = \frac{1}{2} \int_M (\{u^*\}^2 + \{r^*\}^2) \, dM, \]

where \( A_Z, A_L, K_Z, \) and \( K_L \) are zonal available potential energy, eddy available potential energy, zonal kinetic energy and eddy kinetic energy respectively over closed domain (of mass \( M \)) under consideration.

The various energy conversion terms are as follows.

\[ C(A_Z, A_L) = -C_T \int_M \{ \{w^*\} \} \{ \{T\} \} \frac{\partial \{T\}}{\partial y} \, dM \]
\[ + \{ \{w^*\} \} \frac{\partial \{T\}}{\partial p} dM \]

\[ C(A_Z, K_Z) = -R \int_M \left( \int_M \{ [wt] - \{w\} \{T\} - \{T\} \} \, dM \right) \]

\[ C(A_L, K_E) = -R \int_M \frac{1}{M_P} \{ [w^*t^*] \} \, dM \]

\[ C(K_E, K_E) = -\int_M \{ [u^*w^*] \} \frac{\partial \{u\}}{\partial y} + [u^*w^*] \frac{\partial \{u\}}{\partial p} \]
\[ + [e^*w^*] \frac{\partial \{e\}}{\partial y} + [e^*e^*] \frac{\partial \{e\}}{\partial p} \, dM, \]

where \( \gamma = \frac{\partial \theta}{\partial p} \)

where \( \{ \} = \) zonal mean, \( * = \) deviation from the mean, \( \approx = \) global seasonal mean, \( \{ \} = \) average over the limited area.

All other symbols have their usual meaning. Our purpose is to see the various energy transformations of the growing pulse when the basic flow is held constant and CISK type of convective heating is operative.

It was found that \( A_Z \) and \( K_Z \) were constant with time (figure not shown). This is as expected since the basic flow is kept fixed. Figure 8 shows the plots of \( A_Z \) and \( K_Z \) from 1st to 5th day of integration with CISK. \( K_Z \) increases slowly from day 1 to day 3 and increases rapidly afterwards. \( A_Z \) also increases slowly up to day 3 but increases more later on.

Figure 9 shows the conversion of \( A_Z \) to \( A_L, A_E \) to \( K_E \) and \( K_Z \) to \( K_E \) with time. \( C(A_Z, A_L) \) and \( C(A_L, K_E) \) values are large and are of comparable magnitude. Thus there is large baroclinic energy conversion in the presence of cumulus heating. \( C(A_E, K_E) \) is associated with rising of warm air and sinking of cold air (in the east-west plane) which is clearly seen from Figures 6 d and 7 d. From Figure 9 it is seen that the barotropic energy conversion from \( K_Z \) to \( K_E \) is rather small.

Thus from our energy calculations it is clear that the perturbation grows into depression stage by baroclinic energy exchange in presence of cumulus heating. Barotropic energy exchange is rather small.
Conclusions

Our study using summer monsoon type basic flow generated in a global spectral model shows that

- when an incipient vortex is superposed on the low level monsoon type flow in the region of the monsoon trough and cumulus heating is present the vortex grows to depression stage (and further strengthens). The evolving disturbance has many features similar to those of observed monsoon depressions.
- the main growth mechanism is by large-scale baroclinic energy conversions in the presence of cumulus heating.


Received 20 August 1992; accepted 5 December 1992

RESEARCH COMMUNICATIONS

Occurrence of ultramafic breccia in the Aravalli Fold Belt, Rajasthan

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A lensoidal body of serpentine breccia is preserved within the ophiolite melange of the Aravalli Fold Belt at Modi, Rajasthan. The field, petrographic characters and rock association possibly suggest that the breccia is formed as a consequence of tectonic emplacement of the serpentinite during the closing of the Aravalli basin.

The Lower Proterozoic Aravalli Fold Belt (AFB) contains ultramafic rocks distributed in two lineaments, viz. the Rakhavdeh in the east and the Kaligumman in the west. The former coincides with the boundary between the continental shelf and deep sea facies rocks of the Aravalli stratigraphy but the latter is restricted to the deep sea sediments. In both the cases the ultramafic and associated rocks occur as a series of composite slivers and possibly represent ophiolite melanges. Though the serpentinitized ultramafics form the dominant constituent, the other commonly associated lithologies are banded chert, gabbro, pillowed basalt, carbonates and minor granites. The ultramafics have undergone various degrees of serpentinitization and greenschist facies metamorphism. Here we describe a rare occurrence of serpentine breccia from the western lineament as Modi-Madhya ophiolite melange (MMOM). The MMOM forms a band of 100 m to 1.5 km wide and extends for more than 50 km from north of Modi to south of Madha (Figure 1) and possibly joins with the ultramafic band at Jharol. The serpentitized ultramafic rocks in it either form a continuous band or occur as lenses of variable dimensions. The contact of these bodies with the Jharol turbidites is always sharp and very often marked by intense mylonitization. The effect of shearing in the serpentine is rarely preserved but at places a foliation fabric parallel to the contact is well developed. The chert band generally bordering the ultramafic-turbidite contact is intensely sheared and there is a broad parallelism between the mylonite banding and the first foliation (S1) of the country rock. The chert band along with the serpentinite and carbonates is involved in (map scale) second generation folding, thus suggesting the melange emplacement during the first deformation of the country rock.

The serpentine breccia occurs as a lensoidal body (100’ x 20’) within the MMOM about 1.5 km east of Modi (24° 47’ 15”, 73° 33’ 50”). It is fine grained, light greenish in colour and contains uneven fragments of