

## Letters to the Editor

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### BALANCE OF KINETIC ENERGY IN THE FIELD OF MID-TROPOSPHERIC CYCLONE

1. The tropical regions have been considered as the heat source in maintaining the global energy balance of the atmosphere by various numerical studies and general circulation models. For the tropical region, the summer monsoon trough over India and neighbourhood is perhaps the best known quasi-stationary perturbations of the general circulation. The mean pattern of the trough is sometimes distorted by eddies, better known as monsoon depressions (MD's) and also mid-tropospheric cyclones (MTC's). Of these two perturbations, the MDs have been exhaustively, widely & extensively studied by the large number of atmospheric scientists in India as well as abroad. Koteswaram and George (1958), Rao and Rajamani (1970, 1972a, 1972b), Godbole (1975), Keshavamurthy *et al.* (1978), Nitta and Masuda (1981), Saha and Chang (1983) are some of the few names. MDs have attracted primary importance for the study because of this widespread associated rainfall. But MTC is another important synoptic scale system, which gives heavy to very heavy rainfall in western & central parts of India and rather unfortunately, has got less attention though it deserves. Miller and Keshavamurthy (1968) made a comprehensive observational study involving conventional surface and upper air reports, aircraft flight with dropsonde and ship reports, radar and satellite information during I.I.O.E. for period between 1960 & 1965. Their observation and study revealed many structural aspects about the MTCs formed over the north-east Arabian Sea. They showed that Arabian Sea MTCs are cold core below 500 hPa and warm core above. They were of the opinion that MTCs are the principal activators and regulators of rainfall over western India. They computed divergence, vorticity and vertical motion from the streamline analysis, using the centre of MTC at 500 hPa as the origin. They also found that the vorticity increases with the height upto 500 hPa and the slope of the line of the maximum vorticity increases towards south and west.

The estimates of kinetic energy (KE) in the field of the extra-tropical and tropical cyclones have been reported by different research workers (Smith, 1973; Vincent & Chang 1975; Kornegay & Vincent, 1976; Robertson & Smith, 1980). Very few attempts appear to

have been made in Indian region towards analyzing the KE budget of monsoon systems. Anjaneyulu (1971) reported the budget of energy of monsoon trough based on mean data of July & August. Singh *et al.* (1980/81) analyzed the budget of KE over the Indian region utilizing the data of 4 to 9 July 1973, when a good coverage of data was available through special observing platforms in ISMEX-73 experiment. Chen & Wiin Nielsen (1976) have shown that the divergent wind plays an important role in the energetic of the atmosphere.

In this paper, some aspects of kinetic energy have been studied for the average MTC, which forms over the north-east Arabian Sea during the monsoon season.

2. 27 cases of MTC's during the period 1985 to 1990 considered in this study are given in Table 1. These cases have been identified with the help of weekly weather report from the office of Regional Meteorological Centre, Mumbai. Only those cases have been considered, which were seen in the middle troposphere and during months of June, July and August. The upper air data of 0000 UTC have been collected from RS/RW stations for Mumbai, Ahmedabad, Hyderabad, Aurangabad, Panjim, Nagpur, Karachi, Jodhpur and pilot balloon stations such as Pune, Veraval & Bhuj.

For analytical purpose the MTC is taken as axially symmetrical cylinder between 700 hPa & 500 hPa and the average position of 600 hPa as the center of the system, so that the system is divided in to two halves. The radial wind velocity has been computed with the help of method suggested by Jordon (1952) and the method of composition is utilized as suggested by Ruprecht & Gray (1974), Sarkar and Chowdhury (1988).

2.1. A single parameter which is extremely important in evaluating the thermo-dynamic characteristics of any weather system is the distribution of radial velocity ( $V_r$ ) with distance and height. The expression for rate of kinetic energy and mass flux consist of radial velocity and hence accurate determination of this parameter has been done with the method suggested by Jordon (1952). For the present case, the mean radial velocity has been computed for each radial distance and for each standard level. However, the radial transport due

**TABLE 1**  
**Number of Mid Tropospheric Cyclones (MTC's) formed over Gujarat & adjoining NE Arabian sea during the 1985 to 1990**

Year	June		July		August	
	Duration	Level of extension	Duration	Level of extension	Duration	Level of extension
1985	20 - 24	Middle Tropospheric levels	4 - 8 12 - 14	Between 2.1 & 4.5 km a.s.l. Between 2.1 & 3.6 km a.s.l.	9 - 19	Lower & Mid-Tropospheric levels
1986	20 - 25	Middle Tropospheric levels	17 - 20 29 - 31	Between 3.1 & 4.5 km a.s.l. Mid-Tropospheric levels	3 - 6 16 - 18 27 Aug - 3 Sep	Mid - Tropospheric levels Mid & Upper Tropospheric Levels Between 3.1 & 5.8 km a.s.l.
1987	29 Jun - 1 Jul	Between 3.1 & 3.6 km a.s.l.	11 - 14 20 - 26	Mid-Tropospheric levels Lower & Middle Tropospheric levels	8 - 9 18 - 25	Mid-Tropospheric levels Lower & Middle Tropospheric levels
1988	24 Jun - 1 Jul	Mid-Tropospheric levels	11 - 13 17 - 20 28 - 31	Mid-Tropospheric levels Lower & Middle Tropospheric levels Between 3.6 & 5.8 km a.s.l.	16 - 22	Between 3.1 & 5.8 km a.s.l.
1989	20 - 22	Between 3.1 & 5.8 km a.s.l.			14 - 16	Between 3.6 & 5.8 km a.s.l.
	29 Jun - 1 Jul	Between 1.5 & 5.8 km a.s.l.			20 - 24	Between 3.1 & 4.5 km a.s.l.
1990	26 - 30	Between 2.1 & 4.5 km a.s.l.			2 - 3 21 - 22	- Between 3.1 & 5.8 km a.s.l.

to eddy motion has not been considered. The mass flow can be obtained from the mass balance equation as,

$$\int_1 \int_{P_B}^{P_T} V_r dl \frac{dp}{g} \quad (1)$$

Where,  $l$  is the periphery of line integral,

$dl$  is its element,

$g$  is the acceleration due to gravity,

$V_r$  is the radial velocity.

$P_B$  and  $P_T$  are the pressure at the bottom and top of the atmosphere.

The integration is done from surface to 100 hPa level.

Curves in the outflow layer, for which the data were not large enough, were drawn under the following presumptions :

(i) Radial flow becomes zero at 100 hPa (*i.e.* at the top of the atmosphere).

(ii) The mass outflow across any radius exactly balances the mass inflow across that radius.

(iii) For any level the radial mass transport is proportional to the radial velocity.

For different radii, the vertical profiles of the radial flow are given in Fig. 1. It is further assumed that the integral of radial velocity and so the mass flow, from the surface to 100 hPa must vanish for all radii.

The mass flow profiles reveal some interesting features in the field of MTC. The inflow layer is well defined and depth of inflow decreases with height radially outward from the center. The depth of inflow layer near the center of MTC is seen from the surface upto 500 hPa, where as its depth decreases outward radially and is from surface to 600 hPa near 800 km. Inflow in the outer radii (700 & 800 km from the center) are found to be weak compared to that near center and inflow is confined mostly below 600 hPa.

The outflow is found to maximum near 300-200 hPa in the entire field. Near the center the outflow is invariably noticed at 300 hPa. The outflow slopes upwards as the distance increases radially outwards. The changes in the magnitude of inflow and outflow across the adjacent radii are found to be gradual.

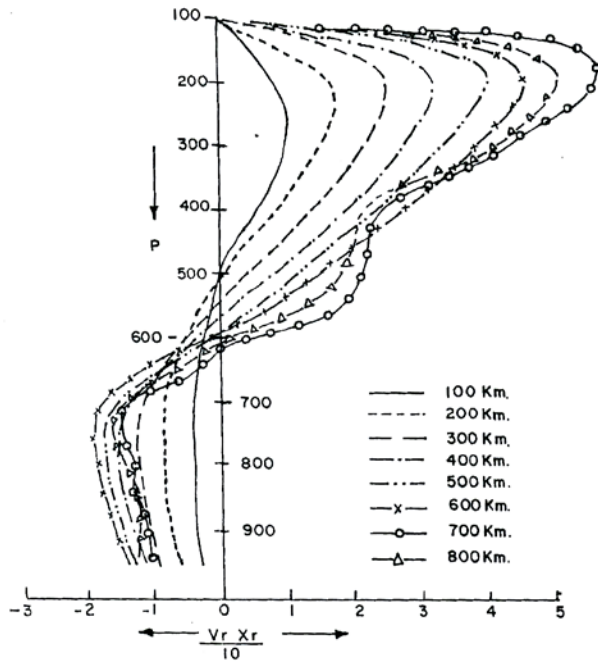


Fig. 1. Vertical profile of radial wind (in the form of  $rVr/10$  in unit :  $10^{10}$   $\text{cm}^2/\text{sec}$ ) against pressure for various radii

If the inflow occurs in the lower troposphere layers, say upto 500 hPa and the outflow in the upper troposphere layers, then in the middle-troposphere there must be an inactive layer (*i.e.*, a layer where neither inflow nor outflow exists). This indicates the absence of cooling in the mid-troposphere. This has been termed as “Ventilation” by Simpson & Riehl (1958).

Thus, the presence of inflow up to 500 hPa and active ventilation in the mid-troposphere perhaps is the necessary condition for the development and maintenance of the synoptic scale systems like depressions, cyclonic storms, MTCs. Riehl and Malkus (1961) also observed that the inflow upto 500 hPa and active ventilation to the mid-troposphere in the hurricanes Daisy (1958) which according to them was a weak cyclone compared to the other Atlantic hurricanes. From a study of monsoon depressions Chowdhury (1983) also found the inflow layers being well defined upto 500 hPa and the outflow between 400 & 300 hPa and the presence of ventilation near 500 hPa. The active ventilation is also seen in the field of MTC as the inflow of air mass in the lower layers & the outflow in the upper layers. This ventilation observed between 600 to 500 hPa levels. The height of ventilation decreases with the radial distance.

2.2. The expression for the rate of kinetic energy generation (RKE), for an annular volume, in cylindrical coordinates, is derived with the help of basic horizontal equation of motion, equation of continuity in pressure

coordinate. It is also assumed that the system is axially symmetric. The expression arrived here is similar to that of Krishnamurti and Hawkins (1970), which can be written as

$$\int_{\infty} \frac{\partial K}{\partial t} d\infty = A + B + C \quad (2)$$

Where,

$$A = -2\pi \int_{P_B}^{P_T} (r_2 V_{r2} K_2 - r_1 V_{r1} K_1) \frac{dp}{g}$$

$$B = -2\pi (r_2^2 - r_1^2) \int_{P_B}^{P_T} V_r \left[ \frac{\partial \phi}{\partial r} \right] \frac{dp}{g}$$

$$C = 2\pi \iint (\vec{V} \cdot \vec{F}) r dr \frac{dp}{g}$$

Where,

$K$  is the kinetic energy (KE) at distance  $r$ ,

$\infty$  is the volume of the cylinder and  $d\infty$  is its element,

$K_1$  and  $K_2$  are kinetic energies at radial distances  $r_1$  and  $r_2$

$V_{r1}$  and  $V_{r2}$  are radial wind at distance and  $r_1$  and  $r_2$ ,

$F$  is the frictional force,

$V$  is the velocity at radial distance  $r$ ,

$\phi$  is the geo-potential

$g$  is the acceleration due to gravity,

$\vec{V} \cdot \vec{F}$  is the dot product between  $V$  and  $F$ ,

$\overline{\frac{\partial \phi}{\partial r}}$  is the average value of  $\frac{\partial \phi}{\partial r}$  between  $r_1$  and  $r_2$

Term A is the differential horizontal advection across radii.

Term B is called the production term indicating the mean value of geo-potential height from radius  $r_1$  &  $r_2$ . The mean value of geo-potential has been worked out.

**TABLE 2**  
**Kinetic energy budget in the mean MTC field**  
 (Units :  $\times 10^{12}$  joule/day)

Layer (hPa)	Mean advection	Mean production	Loss due to friction
<b>100-200 km</b>			
1000-800	0.88	2.77	-3.65
800-600	0.81	4.57	-5.38
600-100	-6.03	-13.13	19.16
1000-100	-4.34	-5.79	10.13
<b>200-300 km</b>			
1000-800	0.39	7.09	-7.48
800-600	0.72	7.19	-7.91
600-100	-7.26	-29.59	36.85
1000-100	-6.15	-15.31	21.46
<b>300-400 km</b>			
1000-800	-0.20	5.36	-5.56
800-600	-0.57	7.40	-6.83
600-100	-8.73	-56.05	64.78
1000-100	-9.50	-43.29	52.79
<b>400-500 km</b>			
1000-800	-0.13	6.96	-6.83
800-600	-0.22	8.02	-7.80
600-100	-8.27	-31.75	40.02
1000-100	-8.62	-16.77	25.39
<b>500-600 km</b>			
1000-800	-0.37	6.18	-5.81
800-600	-0.59	5.91	-5.32
600-100	-5.94	-46.87	52.81
1000-100	-6.90	-34.78	41.68
<b>600-700 km</b>			
1000-800	-0.33	6.00	-5.67
800-600	-0.43	5.40	-4.97
600-100	5.85	25.58	-31.43
1000-100	5.09	36.98	-42.07
<b>700-800 km</b>			
1000-800	-0.26	4.72	-4.46
800-600	-0.35	2.19	-1.84
600-100	3.90	57.81	-61.71
1000-100	3.29	64.72	-68.01

Term C represents the loss of KE due to frictional effects.

Assuming the production of KE on the local scale within the volume is negligible, the advection, the production of KE and the loss due to friction has been worked out. The results of the computation are presented in Table 2.

From this Table 2, it can be seen that the production term is greater in magnitude than the advection term. It is also seen that from the surface up to 600 hPa, the mean production term contributes more for generating KE. The magnitude of this term increases up to 500 kms and then decreases outwards. Between 800 & 600 hPa *i.e.*, region of MTC occurrence, the mean production term goes on increasing upto 500 kms in the field of influence of MTC and then decreases radially outwards. The total KE (*i.e.*, advection term plus production term), is lost in the field of MTC by internal friction and helps to maintain the balance.

3. The following important conclusions on the structure of MTC emerge out of this study:

(i) Inflow predominantly presents below 500 hPa and outflow above it. The outflow spreads at 200-300 hPa, more at the increasing radial distance.

(ii) Presence of active ventilation between 600 hPa and 500 hPa.

(iii) The loss of total KE in the MTC field helps in maintaining the balance.

(iv) The production term of maintaining KE balance is more in magnitude than mean advection term.

(v) There is in general increase in production term radially outward upto 500 km and then decreases.

#### References

- Anjaneyulu, T. S. S. S., 1971, "Estimates of KE over the Indian monsoon trough zone", *Quart. Jour. Rev. Met. Soc.*, **97**, 103-109.
- Chen, T. C. and Wiin Nielson, A., 1976, "On the KE of the divergent and non-divergent flow in the atmosphere", *Tellus*, **28**, 486-498.
- Chowdhury, A., 1983, "On the mass, heat and moisture balance in the field of depression, *Mausam*, **34**, 4, 383-394.
- Godbole, R. V., 1975, "Composite structure of the monsoon depression", Rept. 75-9, Department of Meteorology, Florida state University, Tallahassee, p31.
- Jordan, E. S., 1952, "An observational study of upper wind circulations around tropical storms", *Journal of Meteorology*, **9**, 340-346.
- Kornegay, R. C. and Vincent, D. G., 1976, "The KE budget analysis during interaction of tropical storm Candy (1968) with and extra tropical frontal system", *Mon. Wea. Rev.*, **104**, 849-859.

- Keshavamurthy, R. N., Asnani, G. C., Pillai, P. V. and Das, S. K., 1978, "Some studies of growth of monsoon disturbances", *Proc. Indian Aca. Sci.*, **87**, 61-75.
- Koteswaram, P. and George, C. A., 1958, "On the formation of monsoon depression in Bay of Bengal", *Indian J. Met. Geophys.*, **9**, 9-22.
- Krishnamurti, T. N. and Hawkins, R. S., 1970, "Mid-tropospheric cyclones of southwest monsoon", *Jour. Appl. Meteor.*, **9**, 442-458.
- Miller, F. R. and Keshavamurthy, R. N., 1968, "Structure of an Arabian Sea summer monsoon systems, HIOE, Meteorological monograph, 1, east-west centre press, Honolulu.
- Nitta, T. and Masuda, K., 1981, "Observational study of depressions developed over Bay of Bengal during summer MONEX-79", *Jour. Meteor. Soc.*, Japan, **59**, 672-682.
- Rao, K. V. and Rajamani, S., 1970, "Diagnostic study of monsoon depression by geostrophic baroclinic model", *Indian J. Met. Geophys.*, **21**, 182-194.
- Rao, K. V. and Rajamani, S., 1972a, "Diagnostic study of monsoon depression by numerical methods", *Indian J. Met. Geophys.*, **23**, 247-248.
- Rao, K. V. and Rajamani, S., 1972b, "Study of heat sources and sinks and the generation of available potential energy in the Indian region during southwest monsoon", *Mon. Wea. Rev.*, **100**, 383-388.
- Riehl, H. and Malkus, J., 1961, "The intensity of net meridional circulation", *Quart. Jour. Met. Soc.*, **76**, 182-188.
- Robertson, and Smith, P. J., 1980, "The KE of two severe storms producing extra-tropical cyclones", *Mon. Wea. Rev.*, **108**, 127-143.
- Ruprecht, E. and Gray, W. M., 1974, "Research paper No. 219, Deptt., of Atmos. Sciences, Colorado State University.
- Saha, K. and Chang, C. P., 1983, "The baroclinic processes of monsoon depression", *Mon. Wea. Rev.*, **111**, 1506-1514.
- Sarkar, R. P. and Chowdhury, A., 1988, "A diagnostic structure of monsoon depression, *Mausam*, **39**, 1, 9-18.
- Simpson, R. H. and Riehl, H., 1958, "Mid-tropospheric ventilation a constraint on development & maintenance proceedings, "First Technical Conference on Hurricane", Miami beach, Florida, 19-22 November 1958.
- Singh, S. S., Kulkarni, A. A. and Bandhopadhyaya, 1980/81, "The KE budget of monsoon circulations over the Indian region during ISMET-1973", *PAGEOPH*, **119**, 16-23.
- Smith, P. J., 1973, "The KE budget over north America during a period of major cyclone developments", *Tellus*, **25**, 411-423.
- Vincent, D. G. and Chang, L., 1975, "KE budget of moving system: Case studies of an extra tropical cyclones and hurricane Celia (1970)", *Tellus*, **27**, 215-233.

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