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Contribution of divergent wind component to the kinetic energy budget over the Indian summer monsoon region

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सार — 4-9 जुलाई 1973 की अवधि में मानसून क्षेत्र की गतिज उर्जा पर अपसारी पवन के प्रभाव का अन्वेषण किया गया है। ऊर्जा बजट पदों में अपसारी पवन के योगदान के बारे में अलग से विवरण देकर उसकी विवेचना की गई है। परिणामों से स्पष्ट है कि विभिन्न बजट पदों के आकलन करने में अपसारी पवन के घटक को नगण्य मान लेने से भारी त्रुटि हो सकती है।

ABSTRACT. Effect of divergent wind on the kinetic energy budget over the monsoon region during the period 4-9 July 1973 has been investigated. The contribution of divergent wind to energy budget terms has been presented and discussed separately. The results clearly demonstrate that the neglect of divergent wind may lead to sizeable errors in the evaluation of different budget terms.

1. Introduction

Several studies (Smith 1973; Vincent and Chang 1975; Kornegay and Vincent 1976; Chen *et al.* 1978; Robertson and Smith 1980) have been reported in the literature about kinetic energy budget estimates of extratropical and tropical cyclones. A few attempts have been made in the Indian region to analyse the kinetic energy budget of monsoon systems. Anjaneyulu (1971) reported the energy budget of monsoon trough based on the mean data of July and August. Singh *et al.* (1980/81) analysed the budget over Indian region utilising the data of 4-9 July 1973 when a good coverage of data was collected by special observing platforms during ISMEX-73. These studies utilised the total wind. Chen and Wiin Nielsen (1976) and Chen *et al.* (1978) have shown that the divergent wind plays an important role in the atmospheric energetics. In the present study contribution of divergent wind component to the kinetic energy budget is determined.

2. Kinetic energy budget equation

In (x,y,p,t) coordinate system, the rate of change of kinetic energy in an atmospheric column is

$$\frac{\partial K}{\partial t} = \underset{(a)}{\frac{1}{Ag}\int_0^{P_0}\int_A \frac{\partial K}{\partial t}\, dA\, dp}$$

$$= \underset{(b)}{-\frac{1}{Ag}\int_0^{P_0}\int_A \nabla.(\mathbf{V}K)\, dA dp} \underset{(c)}{-\frac{1}{Ag}\int_0^{P_0}\int_A \frac{\partial}{\partial P}(\omega K)\, dA\, dp} \underset{(d)}{-\frac{1}{Ag}\int_0^{P_0}\int_A \mathbf{V}.\nabla\phi\, dA dp} + \underset{(e)}{D(K)} \quad (1)$$

where A is the area of computational domain, ϕ $(=gz)$ is the geopotential, P_0 is the surface pressure, $K = \left(\frac{u^2+v^2}{2}\right)$ the horizontal kinetic energy per unit mass. The terms on the right hand side are the horizontal flux divergence, vertical flux divergence, generation and dissipation of kinetic energy respectively.

The total wind vector $\mathbf{V}$ is the sum of nondivergent wind $(\mathbf{V}_R)$ and divergent wind $(\mathbf{V}_D)$, *i. e.*,

$$\mathbf{V} = \mathbf{V}_R + \mathbf{V}_D \quad (2)$$

The kinetic energy K_R and K_D may be expressed as

$$K_R = \tfrac{1}{2}\mathbf{V}_R^2,\ \ K_D = \tfrac{1}{2}\mathbf{V}_D^2 \quad (3)$$

And the kinetic energy K in terms of K_R and K_D is

$$K = K_R + K_D + \mathbf{V}_R \,.\, \mathbf{V}_D \quad (4)$$

Application of Eqn. (2) in the integrands of the first and third terms on the right hand side of (1) gives

$$-\nabla\,.\,(\mathbf{V}K) = -\nabla\,.\,(\mathbf{V}_R K) - \nabla\,.\,(\mathbf{V}_D K) \quad (5)$$

$$-\mathbf{V}\,.\,\nabla\phi = -\mathbf{V}_R.\ \nabla\phi - \mathbf{V}_D.\ \nabla\phi \quad (6)$$

Using Eqns. (5) and (6), (1) can be rewritten as

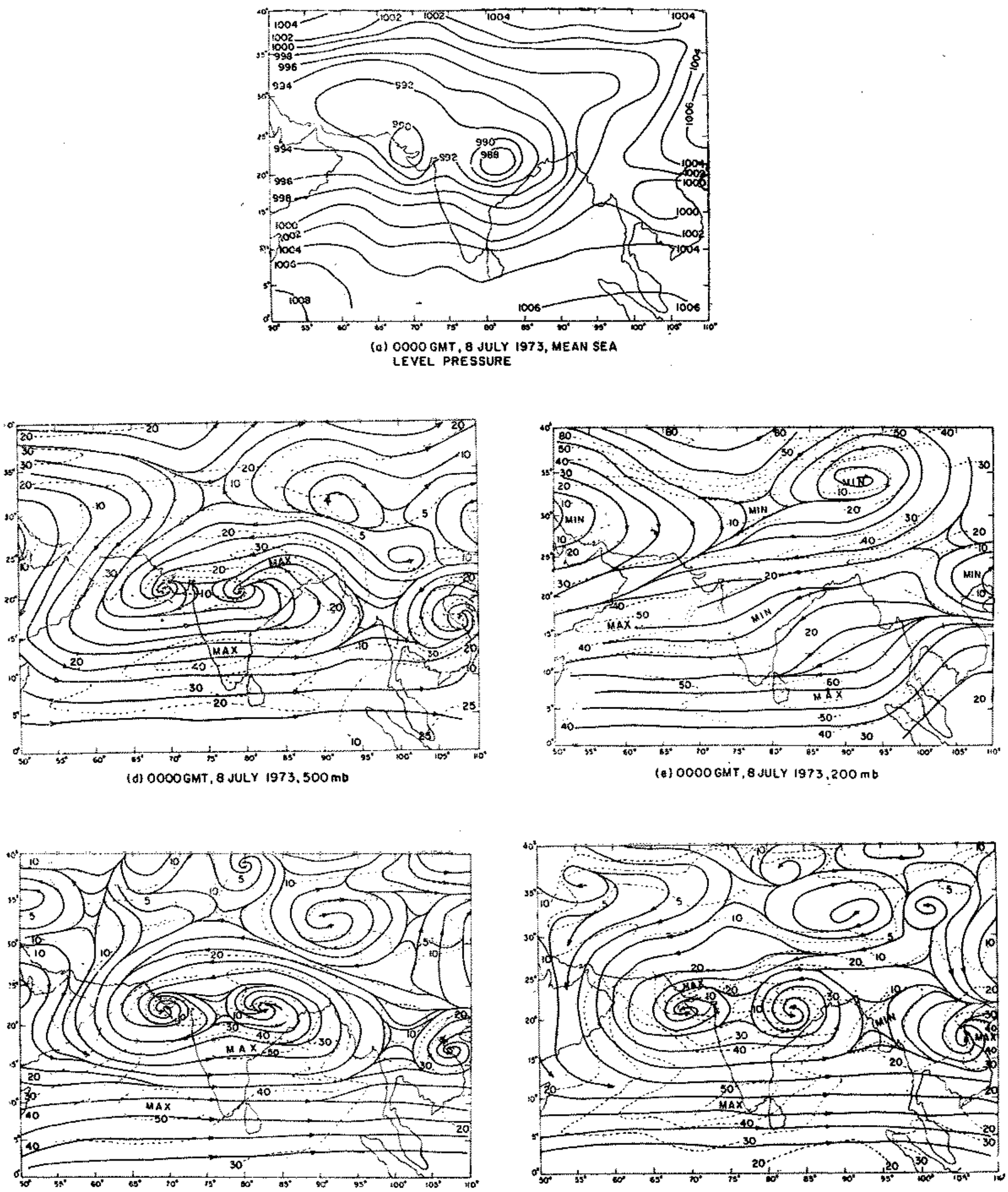

Fig. 1. Flow charts at 00 GMT, 8 July 1973, : (a) Mean sea level pressure analysis; stream line and isotach analysis at (b) 850 mb, (c) 700 mb (d), 500 mb and (e) 200 mb

$$\frac{1}{Ag}\int_0^{P_0}\int_A \frac{\partial K}{\partial t}\, dA\, dp =$$

$$-\frac{1}{Ag}\int_0^{P_0}\int_A \nabla\cdot(\mathbf{V}_R K)\, dA\, dp$$

$$-\frac{1}{Ag}\int_0^{P_0}\int_A \nabla\cdot(\mathbf{V}_D K)\, dA\, dp$$

$$-\frac{1}{Ag}\int_0^{P_0}\int_A \mathbf{V}_R\cdot\nabla\phi\, dA\, dp$$

$$-\frac{1}{Ag}\int_0^{P_0}\int_A \mathbf{V}_D\cdot\nabla\phi\, dA\, dp$$

$$-\frac{1}{Ag}\int_0^{P_0}\int_A \frac{\partial}{\partial p}(\omega K)\, dA\, dp + D(K) \quad (7)$$

If the divergent wind is neglected, Eqn. (7) becomes

$$\frac{1}{Ag}\int_0^{P_0}\int_A \frac{\partial K}{\partial t} dA\, dp = -\frac{1}{Ag}\int_0^{P_0}\int_A \nabla\cdot(\mathbf{V}_R K)\, dA\, dp$$

$$-\frac{1}{Ag}\int_0^{P_0}\int_A \mathbf{V}_R\cdot\nabla\phi\, dA\, dp - \frac{1}{Ag}\int_0^{P_0}\int_A \frac{\partial}{\partial p}(\omega K) dA\, dp +$$

$$+ D(K) \quad (8)$$

From Eqn. (8) the effect on the kinetic energy budget due to neglect of divergent wind could be calculated.

3. Data and method of computation

Data of 00 GMT 4 July through 00 GMT 9 July 1973 were used for the present study. During this period the twin monsoon depression was the dominant synoptic feature — One in the Bay of Bengal and the other in the Arabian Sea. It is rather a rare phenomenon that the two depressions formed and intensified simultaneously. During this period additional data over the oceanic region was also collected by research oceanic vessels belonging to the ISMEX-1973.

The streamline, isotach and temperature analysis were carried out manually at the surface ($\sim$ 1000 mb), 850, 700, 500, 300, 200 and 100 mb. In addition to this, the mean sea level (msl) pressure was also analysed. Fig. 1 presents the mean sea level pressure analysis; streamline and isotach analysis at 850, 700, 500 and 200 mb of 00 GMT, 8 July 1973. The computational domain extends from 50° to 110°E and 2° to 40°N and in the vertical plane from the surface to 100 mb. Wind direction, speed and temperature data were interpolated on a uniform grid of 220 km ($\Delta x = \Delta y =$ 220 km) on Mercator projection. A correction term, the map factor (Secant of latitude) corresponding to Mercator projection was included in evaluating the kinetic energy budget terms. The u and v components were obtained from the observed wind speed and direction. The computations were done at the surface, 800, 600, 400, 200, and 100 mb respectively. The data at 800, 600, and 400 mb were interpolated linearly from the data of two adjacent levels. Similarly, temperature was also interpolated at 900 mb. Geopotential heights were constructed using the hydrostatic relation beginning from the surface.

The vertical velocity was computed from the continuity equation using the observed wind data, with the modification that the net divergence in a vertical column is zero. It may be appropriate to mention here that this method of computation was preferred as a result of an investigation made by Smith and Lin (1978). The vanishing of the vertical integral of divergence obviously makes the vertical velocity zero at the surface (lower boundary) and at the 100 mb (upper boundary). This method of computation does not include the effect of topography, but its effect is partially eliminated by the vertical differencing as used in the computation of the vertical flux divergence term.

For studying the impact of divergent wind on the kinetic energy budget the wind was separated into non-divergent and divergent components. The non-divergent wind was computed by an iterative method (Endlich 1967). This method is briefly described as follows :

The vorticity is calculated from the analysed grid point wind by simple centred differences. Let a grid point's nearest neighbours to the east, west, north and south be denoted as e, w, n and s respectively. The corrections of equal magnitude but opposite sign are then made to u_e and u_w, and similarly to v_n and v_s so that the divergence at the central grid point becomes zero. This adjustment at each grid point of domain will naturally modify the original vorticity field, but a second round of adjustments involving u_n, u_s, v_e, v_w at each grid point can bring them into closer agreement with the original vorticity. The method just described is repeated till the divergence becomes negligibly small and vorticity remains closer to the original wind. Finally, a constant correction is added to the u and v components of the final adjusted wind so that the average values of the non-divergent wind agree with the average values of the observed wind. The vector difference of observed wind and non-divergent wind gives the divergent wind.

The change in kinetic energy term was evaluated as a simple difference between the kinetic energy (K) for two consecutive map times. This represents the rate of change of kinetic energy over a 24-hour period. The terms (b), (c) and (d) were computed at each map time using a centred difference in space, and averaged over two consecutive map times to represent the mean over a 24 h period. Term (e) was computed as a residual to balance the kinetic energy Equation (1). These operations were performed at each grid point for all the levels. Then each term was vertically integrated using the trapezoidal rule. The area average quantities were determined giving equal weight to each point. The original data as well as computed energy terms were not subjected to any kind of explicit smoothing, except that the data were manually checked for horizontal and vertical consistency.

TABLE 1

Vertically integrated (surface to 100 mb) kinetic energy budget

(Unit : 10^5 Jm^{-2} for K and 10^{-1} Wm^{-2} for other quantities)

Date/Time	K	$\frac{\partial K}{\partial t}$	$-\nabla.(\mathbf{V}K)$	$-\mathbf{V}.\nabla\phi$	D
4-5/00	66.9	13.7	13.5	31.3	—31.1
5-6/00	66.9	—13.5	1.2	41.9	—56.7
6-7/00	65.3	9.6	—6.6	56.6	—40.4
7-8/00	75.3	13.4	—5.5	90.4	—71.6
8-9/00	75.5	—12.6	—6.1	91.4	—97.9
Average	70.0	2.1	—0.7	62.3	—59.5

TABLE 2

Time mean kinetic energy budget at different pressure layers

(Unit : 10^4 Jm^{-2} for K and 10^{-1} Wm^{-2} for other quantities)

Pressure layers (mb)	K	$\frac{\partial K}{\partial t}$	$-\nabla.(\mathbf{V}K)$	$-\frac{\partial}{\partial p}(\omega K)$	$-\mathbf{V}.\nabla\phi$	D
100-200	19.4	—0.4	—4.1	0.9	18.6	—15.8
200-400	21.7	0.4	—1.4	—0.3	11.2	—9.1
400-600	8.8	0.4	1.7	1.2	3.5	—6.0
600-800	10.9	1.1	1.2	—0.3	10.3	10.1
800-Surface	9.2	0.6	1.9	—1.5	18.7	18.5
Integrated	70.0	2.1	—0.7	0.0	62.3	—59.5

TABLE 3

Vertically integrated kinetic energies K, K_R, K_D and $\mathbf{V}_R.\mathbf{V}_D$ and ratios K_R/K, K_D/K, $\mathbf{V}_R.\mathbf{V}_D/K$ for 4-9 July 1973

(Unit : 10^5 Jm^{-2})

Date/Time	K	K_R	K_D	$\mathbf{V}_R.\mathbf{V}_D$	K_R/K	K_D/K	$\mathbf{V}_R.\mathbf{V}_D/K$
4-5/00	66.9	61.5	18.4	—13.0	91.9 %	27.5%	—19.4%
5-6/00	66.9	63.1	22.5	—18.7	94.3 %	33.6%	—27.9%
6-7/00	65.3	60.8	25.8	—21. 3	93.1%	39.5%	—32.6%
7-8/00	75.3	70.4	32.3	— 27.4	93.5%	42.9%	—36.4%
8-9/00	75.5	69.1	30.3	—23.9	91.5%	40.1%	—31.6%
Average	70.0	65.0	25.9	—20.9	92.9%	36.7%	—29.6%

TABLE 4

Kinetic energies K, K_R, K_D and $\mathbf{V}_R.\mathbf{V}_D$ as a function of pressure

(Unit : 10^4 Jm^{-2})

Pressure layers (mb)	K	K_R	K_D	$\mathbf{V}_R.\mathbf{V}_D$
100-200	19.4	18.0	5.2	—3.8
200-400	21.7	20.0	8.9	—7.2
400-600	8.8	8.6	4.2	—4.0
600-800	10.9	9.8	3.5	— 2.4
800-Surface	9.2	8.6	4.1	—3.5
Integrated	70.0	65.0	25.9	—20.9

TABLE 5

Vertically integrated kinetic energy flux divergence of the total wind, non-divergent wind, divergent wind

(Unit : 10^{-1} W m^{-2})

Date/Time	$-\nabla.(\mathbf{V}K)$	$-\nabla.(\mathbf{V}_R K)$	$-\nabla.(\mathbf{V}_D K)$
4-5/00	13.5	13.7	—0.2
5-6/00	1.2	—8.3	9.5
6-7/00	—6.6	—1.7	—4.9
7-8/00	—5.5	—1.7	—3.8
8-9/00	—6.1	—12.3	6.2
Average	—0.7	—2.1	1.4

The different kinetic energy budget terms of Eqns. (7) and (8) were also computed in a similar manner described above.

4. Kinetic energy budget

Kinetic energy budget for the monsoon region from 4 - 9 July 1973 has been discussed by Singh *et al.* (1980/81) and the objective of the present study is to analyse the effects of divergent wind on the budget of the same depression. For the sake of continuity, the results of the total wind are presented in Tables 1 and 2. It may be noted that the values of the different kinetic energy terms are slightly modified due to slight revisions in the analysis, from those presented in earlier study (Singh *et al.* 1980/81). However, the basic conclusion regarding direction of source and sinks of energy remain unaltered.

5. Contribution of divergent and nondivergent wind components to the kinetic energy budget

5.1. *Kinetic energy budget*

The kinetic energy of divergent wind on planetary scale motion may be insignificant, but not necessarily for the synoptic scale systems with regions of intense cyclogenesis. Table 3 depicts the contribution of the divergent wind ratios K_R/K, K_D/K and $\mathbf{V}_R.\mathbf{V}_D/K$

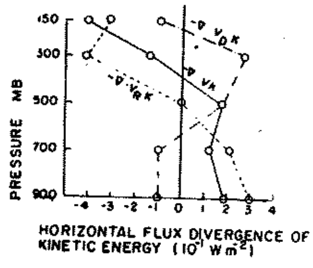

Fig. 2. Time averaged K.E. flux divergence of the total wind (stragiht line)

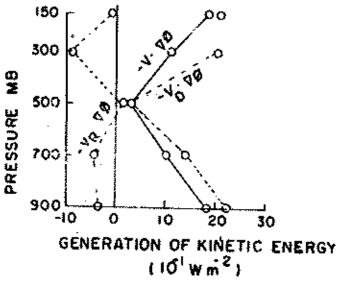

Fig. 3. Time averaged generation of K.E. by the total wind (straight line)

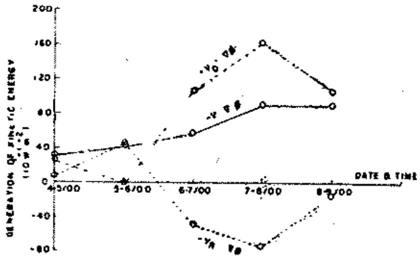

Fig.4. Vertically integrated K.E. generation by the total wind (straight line)

- - - - - - (dashed line). Non-divergent wind, ... (Dotted line). Divergent wind

during the period from 4-9 July 1973. Generally K, K_R and K_D vary in the same direction with a few exceptions. The dot product of non-divergent and divergent winds $\mathbf{V}_R \cdot \mathbf{V}_D$ is always negative. It may be seen from Table 3 that the percentage ratio of K_D to K is as large as 42% on 7-8 July. Table 4 gives the time mean kinetic energy at different levels. The maximum of K, K_R, K_D and $\mathbf{V}_R.\mathbf{V}_D$ coincides with the wind maxima at 200-400 mb.

5.2. *Horizontal flux divergence of kinetic energy*

The horizontal flux divergence represents the net flow of kinetic energy in or out of the domain. The total flux divergence of kinetic energy is split into two parts — one due to the non-divergent wind and the other due to the divergent component. The time mean of these quantities are shown in Fig. 2. The horizontal flux divergence $-\nabla.(\mathbf{V}K)$ and $-\nabla.(\mathbf{V}_R K)$ vary with pressure in more or less the same manner and are positive upto 500 mb and negative thereafter, whereas $-\nabla.(\mathbf{V}_D K)$ is negative and small upto 650 mb and positive beyond 650 mb except at the top of the model atmosphere. Table 5 gives the vertically integrated horizontal kinetic energy flux divergnce for the period from 4-9 July 1973. It is evident from Table 5 that the estimation of horizontal flux divergence by neglecting the contribution of the divergent wind may lead to sizeable errors; on the average there is a net loss of kinetic energy which could not be compensated by the positive contribution from the divergent component.

5.3. *Generation of kinetic energy*

The terms $-\mathbf{V}_R.\nabla\phi$ and $-\mathbf{V}_D.\nabla\phi$ are regarded as kinetic energy generations due to barotropic and baroclinic processes respectively (Pearce 1974). Fig. 4 depicts generation of kinetic energy at different times. It is seen from Fig. 4 that during most of the period the baroclinic term is positive and barotropic term is nagative ; thus these two processes are opposed to each other. However, the magnitude of the baroclinic term overcompensates the barotropic term resulting in a significant net generation of kinetic energy. The positive value of baroclinic term suggests the conversion of available potential energy into kinetic energy, whereas a negative barotropic term suggests the opposite process.

Fig. 3 gives the time average generation of kinetic energy for total wind, nondivergent wind and divergent wind. The generation due to total wind and divergent wind remain positive for the entire depth of the atmosphere acting as a source of energy but the generation due to barotropic processes is negative throughout, acting in the opposite sense. The generation due to $-\mathbf{V}.\nabla\phi$, $-\mathbf{V}_R.\nabla\phi$ and $-\mathbf{V}_D.\nabla\phi$ is minium in middle troposphere at 500 mb and maximum in the upper and lower troposphere.

The positive values of $-\mathbf{V}.\nabla\phi$ and $-\mathbf{V}_D.\nabla\phi$ suggests that both total and divergent components represent cross contour flow towards lower pressure whereas the nondivergent wind represents the cross contour flow towards higher pressure.

6. Conclusions

The results demonstrate the important contribution of divergent wind to different energy terms for a case studied over the Indian summer monsoon region. It is found that the neglect of the divergent wind may lead to sizeable errors in the evaluation of the different terms.

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