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Energetics of the monsoon circulation over south Asia — II : Energy terms and energy transformation terms

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सार — दक्षिण एशिया क्षेत्र में जुलाई 1963 में एक विशेष प्रकार का मानसून आया था जिसकी विभिन्न मौसम प्रणालियों को उपलब्ध विभव ऊर्जा तथा उसके गतिज ऊर्जा में स्थानान्तरण का अध्ययन इस शोध पत्र में किया गया । स्थाई भंवरों तथा क्षणिक भंवरों के ऊर्जा-विज्ञान को अलग-अलग अभिकलित कर लिया गया है । उनके बीच अन्योन्य क्रिया तथा उनकी माध्य क्षेत्रीय प्रवाह के साथ क्रिया का भी अध्ययन किया गया है ।

ऐसा अनुमान है कि स्थाई एवं क्षणिक भंवरों के लिये उपलब्ध विभव ऊर्जा का स्त्रोत क्षेत्रीय तरंग है, क्षेत्रीय तरंग तथा क्षणिक भंवरों के लिये गतिज ऊर्जा का स्त्रोत स्थाई भंवर है तथापि जब मानसून द्रोणी पर विचार किया जाता है, स्थाई भंवर क्षणिक भंवर से ऊर्जा प्राप्त करती है और मानसून द्रोणी को सुदृढ़ करने में मानसून अवदाबों का महत्व दर्शाती है । क्षेत्रीय तरंग तथा स्थाई भंवर में मामलों में उपलब्ध विभव ऊर्जा, गतिज ऊर्जा में परिवर्तित हो जाती है । विभव ऊर्जा का पैदा होना तथा लाभ के क्षेत्र में अभिवहित ऊर्जा दोनों मिलकर गतिज ऊर्जा के अपव्यय से हुई हानि से अधिक है ।

ABSTRACT. In this paper a study has been made of available potential energy ond its transformation into kinetic energy of the different weather systems for the region of south Asia for the typical monsoon month of July 1963. Energetics of the standing eddies and transient eddies have been separately computed. Interactions amongst themselves and with mean zonal flow have been studied

It is inferred that zonal current is the source of available potential energy for both standing and transient eddies; standing eddy is the source of kinetic energy for zonal current and transient eddies. However, when the region of monsoon trough is considered, standing eddy gains kinetic energy from transient eddy suggesting the importance of monsoon depressions in strengthening the monsoon trough. Available potential energy is converted into kinetic energy in the cases of both zonal current and the standing eddy. The generation of available potential energy and the energy advected into the area of interest, together exceed the losses due to dissipation of kinetic energy.

1. Introduction

This study pertains to the energy aspects of the monsoon circulation. In the first part of the paper (hereafter called I) the diabatic heating and the generation of available potential energy computed over the monsoon region have been discussed. In the present paper which forms part II of the study, the energy terms, their fluxes, the energy conversion terms and the dissipation of kinetic energy are computed for the typical monsoon month of July. As mentioned in I, monsoon circulation is considered as the mean zonal flow with the standing eddies and the transient eddies superimposed on it. The energetics of the standing eddies and the transient eddies have been separately computed and studied, to understand the interaction amongst themselves and their interactions with the mean zonal flow. As only a limited region is considered, the various energy fluxes have been computed. To complete the energy flow diagram a rough estimate of the frictional dissipation of kinetic energy also has been made.

2. Data

From the daily aerological data of July 1963 from about 90 stations (Details given in I), the following quantities were calculated for the standard isobaric levels, *viz.*, 1000, 850, 700, 500, 300 and 100 mb for each of the stations.

(*i*) Mean monthly temperature, $\overline{T}$

(*ii*) Mean zonal and meridional wind components, $\overline{u}$ and $\overline{v}$.

(*iii*) The variances, $\overline{T'^2}$, $\overline{u'^2}$, and $\overline{v'^2}$

(*iv*) The covariances, $\overline{u'\,v'}$, $\overline{u'\,T'}$, and $\overline{v'\,T'}$

The parameters $\overline{u'^2}$, $\overline{v'^2}$, $\overline{u'\,v'}$, $\overline{u'\,T'}$ and $\overline{v'\,T'}$ were not computed for 1000 and 100 mb levels for want of reliable data. The above nine parameters were plotted on separate charts for all the levels and analysed. The values at the grid points at the intervals of 2.5° latitude and longitude were picked up from the analysed charts. These grid point values have been used in the computation of energetics of the monsoon circulation.

The mean temperature of July 1963 for all stations in the northern hemisphere published in "*Monthly Climatic Data for the World*" were used to compute the hemispherical mean of time mean of temperature, $\tilde{\overline{T}}$ at all standard levels which were used in the computations of zonal available potential energy.

3. Computation of energetics

3.1. Energy terms and their fluxes

Following Lorenz (1955), we write for the total available potential energy, A:

$$A = \int_M \frac{1}{2\tilde{\sigma}} \left(\frac{R}{P}\right)^2 \tilde{T}''^2 \, dM \tag{1}$$

where,

$$\tilde{\sigma} = -\tilde{\alpha} \frac{\partial}{\partial p} \ln \tilde{\theta} \text{ and } \tilde{T}''^2 = \left(\overline{T} - \tilde{T}\right)^2$$

($\frown$) represents hemispherical mean (Symbols are explained in Appendix). Considering mixed space-time domain (Oort 1964), from Eqn. 1, the expressions for zonal, standing eddy and transient eddy available potential energy can be written as :

$$A_Z = \int_M \frac{1}{2\tilde{\sigma}} \left(\frac{R}{P}\right)^2 \left[\ \overline{T}\ \right]''^2 dM \tag{2}$$

$$A_S = \int_M \frac{1}{2\tilde{\sigma}} \left(\frac{R}{P}\right)^2 \left[\ \overline{T}^{*2}\ \right] dM \tag{3}$$

$$A_T = \int_M \frac{1}{2\tilde{\sigma}} \left(\frac{R}{P}\right)^2 \overline{T'^2} \ \ dM \tag{4}$$

where,

$$[\ \overline{T}\ ]''^2 = (\ [\ \overline{T}\ ] - \tilde{\overline{T}}\ )^2 \tag{5a}$$

$$[\ \overline{T^{*2}}\ ] = [(\ \overline{T} - [\ \overline{T}\ ]^2)] \tag{5b}$$

and

$$\overline{T'^2} = (\ \overline{T - \overline{T}}\ )^2 \tag{5c}$$

In Eqn. 5 , $[\ \overline{T}\ ]''^2$ is the mean north-south temperature variance and is proportional to zonal available potential energy, $[\ \overline{T}^{*2}\ ]$ is the east-west mean temperature variance and is proportional to the standing eddy available potential energy and lastly $\overline{T'^2}$ is proportional to transient eddy available potential energy.

In order to calculate the hemispherical mean of the monthly mean temperature, $\tilde{\overline{T}}$ for July 1963 (used in Eqn. 5a), the mean temperatures for July 1963 at all standard levels for all stations in the northern hemisphere published in "*Monthly Climatic Data for the World*" (Sponsored by W. M. O. in cooperation with U. S. Weather Bureau) were used. The temperatures at any level for those stations within 10° latitudinal belts, like equator to 10° N, 10° to 20° N etc were algebraically averaged to represent the respective zonal belt. These zonal mean temperatures, $[\ \overline{T}\ ]$ were further averaged meridionally using the following formula to get the hemispherical mean of time mean temperature, $\tilde{\mathrm{T}}$:

$$i.e.,\ \tilde{\overline{T}} = \frac{1}{\int_0^{\pi/2} a^2 \cos\phi \, d\phi} \int_0^{\pi/2} a^2\, [\overline{T}] \cos\phi \, d\phi.$$

As we have considered a limited area and not the entire globe, following Smith (1969) and Vincent and Chang (1973) we have split the expression for A_Z into two components A_{Zb} and A_{Zc} representing baratropic and baroclinic contributions, so that

$$A_Z = A_{Zb} + A_{Zc} \tag{2a}$$

where,

$$A_{Zb} = \int_M \frac{1}{2\tilde{\sigma}} \left(\frac{R}{P}\right)^2 \left(\{\overline{T}\} - \tilde{\overline{T}}\right)^2 dM \tag{2b}$$

$$A_{Zc} = \int_M \frac{1}{2\tilde{\sigma}} \left(\frac{R}{P}\right)^2 \left([\overline{T}] - \{\overline{T}\}\right)^2 dM \tag{2c}$$

In this study, A_{Zc} the baroclinic contribution to zonal available potential energy, the standing eddy and transient eddy available potential energy [Eqns. (2a), (3) and (4)] are computed using $\{\overline{\sigma}\}$ the mean static stability over the area, instead of $\tilde{\sigma}$, the hemispherical mean static stability in order to avoid some unimportant extra terms entering the expressions for the conversion terms.

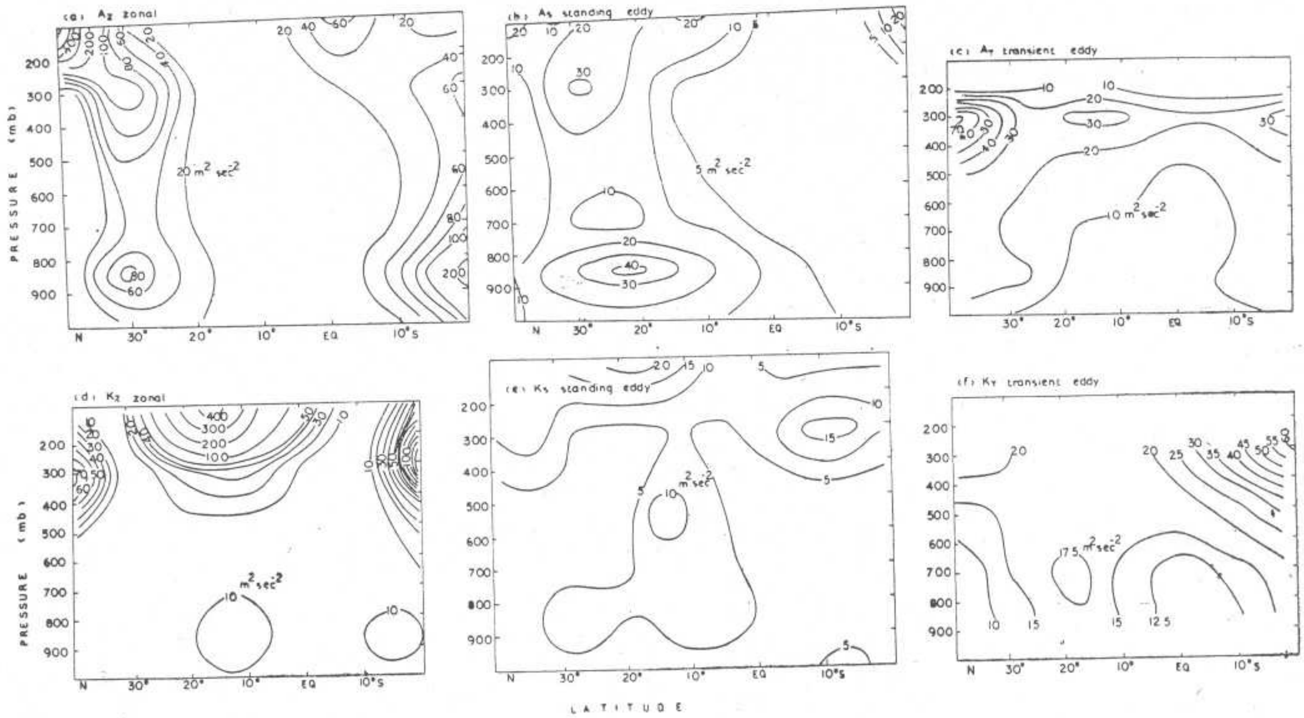
Zonal, standing eddy and transient eddy kinetic energy are represented by the following equations:

$$K_Z = \int_M \tfrac{1}{2} \left([\ \overline{u}\ ]^2 + [\ \overline{v}\ ]^2\right) dM \tag{6}$$

$$K_S = \int_M \tfrac{1}{2} \left([\ \overline{u}^{*2}] + [\ \overline{v}^{\ *2}]\right) dM \tag{7}$$

$$K_T = \int_M \tfrac{1}{2} \left(\overline{u'^2} + \overline{v'^2}\right) dM \tag{8}$$

Available potential energy and kinetic energy in the three forms were computed using appropriate equations given above, for all the standard isobaric levels. Fig. 1 depicts vertical cross-sections for the integrands of these equations. The various energy terms corresponding to layers like 1000-850 mb, 850-700 mb etc were calculated and integrated vertically to obtain the values for the troposphere from 1000 to 100 mb. For this purpose the area is limited to 5° N in south although the values are available upto 20° S (as the analyses south of 5° N have been based on meagre observations).



Figs. 1 (a-f). (a) Zonal available potential energy, (b) Standing eddy available potential energy, (c) Transient eddy available potential energy, (d) Zonal kinetic energy, (e) Standing eddy kinetic energy & (f) Transient eddy kinetic energy (units : m^2/s^2)

TABLE 1

Flux of energy terms (Units : 10^{-2} J m^{-2} s^{-1})

Term	1000 – 850 mb	850 – 700 mb	700 – 500 mb	500 – 300 mb	300 – 100 mb	1000 – 100 mb
A_{Zc}	−2.6	0.1	2.2	4.5	−41.3	−37.1
A_S	−2.2	−0.5	0.9	−2.2	−5.8	−9.8
A_T	−1.4	2.8	5.1	8.7	3.9	19.1
K_Z	−1.4	0.7	1.5	6.2	10.3	17.3
K_S	−1.0	0.9	3.4	1.1	−5.8	−1.4
K_T	−3.0	−3.1	0.2	−3.6	−3.8	−13.3

Since only a limited region is considered in this study, the fluxes of the available potential energy, and kinetic energy (*e.g.*, Smith 1969) have to be computed. Flux of x (where x is an energy term) is given by the following equation :

$$\text{Flux of } x = \oint_L V_n \, x \, dL \tag{9}$$

where V_n is the velocity along outward directed normal. Computation of the fluxes of the energy from Eqn. 9 involves triple correlations in case of transient eddies. In order to avoid this, the fluxes by mean wind $\overline{V}_n$ have been computed, *i.e.*, by the expression, $\oint_L \overline{V}_n \, x \, dL$. Table 1 gives the computed values of the flux of energy terms.

3.2. *Energy conversion terms*

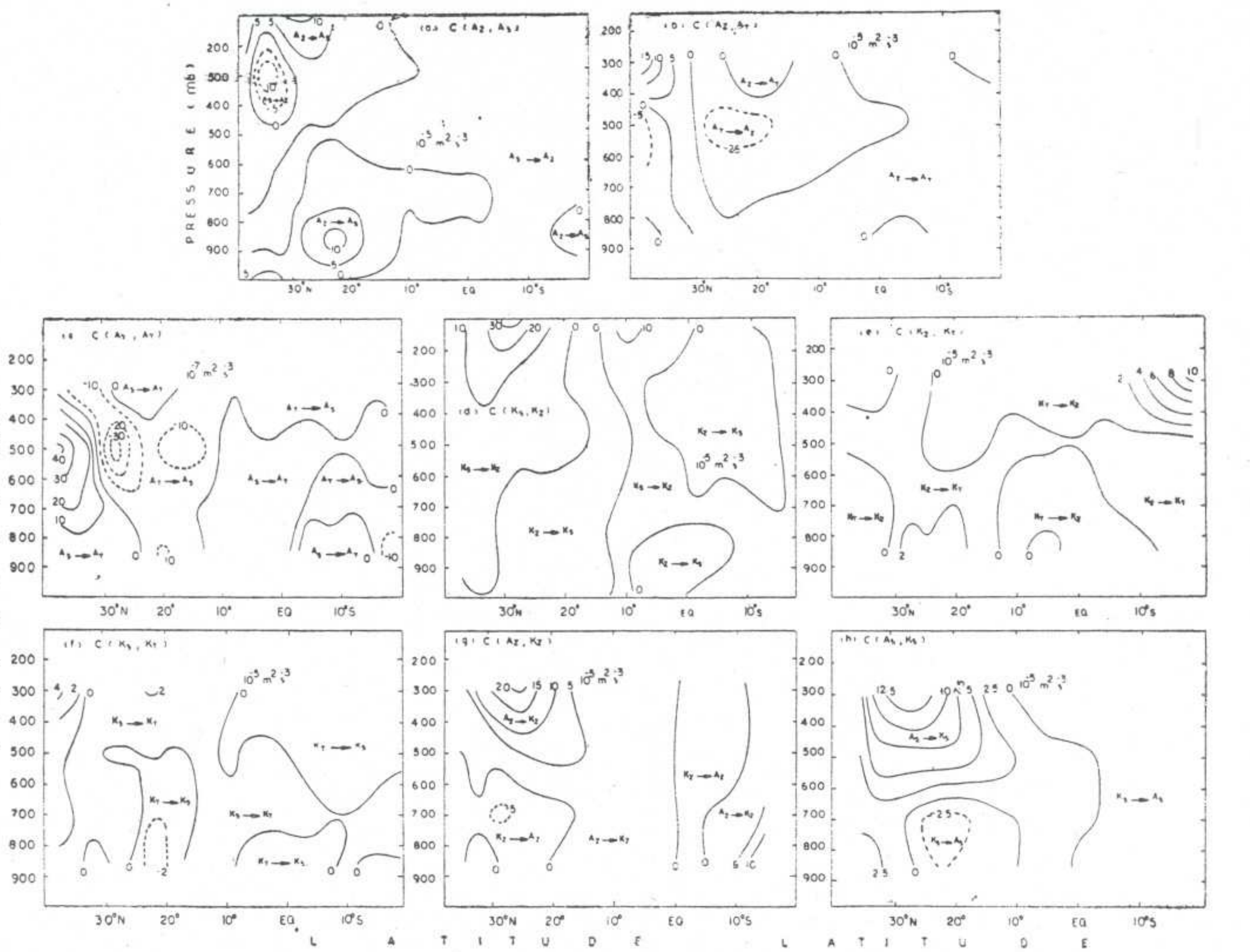
Having computed the energy terms, we now compute the conversion terms, in order to study the entire energetics of the system. The various energy conversion terms were computed using the following relations, Eqns. 10-17 (Oort 1964; Holopainen 1970; Newell *et al.* 1970, 1974; Murakami 1960, 1963 and Krishnamurti *et al.* 1976).

$$C\,(A_Z, A_S) = -\int_M \frac{1}{\{\bar{\sigma}\}} \left(\frac{R}{P}\right)^2 [\bar{v}^* \bar{T}^*] \frac{\partial}{\partial y} [\bar{T}] \, dM \tag{10}$$

$$C\,(A_Z, A_T) = -\int_M \frac{1}{\{\bar{\sigma}\}} \left(\frac{R}{P}\right)^2 \overline{v' T'} \frac{\partial}{\partial y} [\bar{T}] \, dM \tag{11}$$

$$C\,(A_S, A_T) = -\int_M \frac{1}{\{\bar{\sigma}\}} \left(\frac{R}{P}\right)^2 \left(\overline{u' T'} \frac{\partial \bar{T}^*}{\partial x} + \overline{v' T'} \frac{\partial \bar{T}^*}{\partial y}\right) dM \tag{12}$$

$$C\,(K_Z, K_S) = -\int_M \left([\bar{u}^* \bar{v}^*] \frac{\partial}{\partial y} [\bar{u}] + [\bar{v}^{*2}] \frac{\partial}{\partial y} [\bar{v}] \right) dM \tag{13}$$



Figs. 2(a-h). (a) Conversion of available potential energy from zonal current to standing eddy $(m^2/s^3)\times10^{-5}$, (b) Conversion of available potential energy from zonal current to transient eddy $(m^2/s^3)\times10^{-5}$, (c) Conversion of available potential energy from standing eddy to transient eddy $(m^2/s^3)\times10^{-7}$, (d) Conversion of kinetic energy from standing eddy to zonal current $(m^2/s^3)\times10^{-5}$, (e) Conversion of kinetic energy from zonal current to transient eddy $(m^2/s^3)\times10^{-5}$, (f) Conversion of kinetic energy from standing eddy to transient eddy $(m^2/s^3)\times10^{-5}$, (g) Conversion of zonal available potential energy to zonal kinetic energy $(m^2/s^3)\times10^{-5}$ & (h) Conversion of standing eddy available potential energy to standing eddy kinetic energy $(m^2/s^3)\times10^{-5}$

$$C(K_Z, K_T) = -\int_M \left(\overline{u'v'}\ \frac{\partial\,[\bar{u}]}{\partial y} + [\overline{v'^2}]\ \frac{\partial\,[\bar{v}]}{\partial y}\right) dM \qquad (14)$$

$$C(K_S, K_T) = -\int_M \left(\bar{u}^*\left(\frac{\partial\,\overline{u'^2}}{\partial x} + \frac{\partial\,\overline{u'v'}}{\partial y}\right) + \bar{v}^*\left(\frac{\partial\,\overline{u'v'}}{\partial x} + \frac{\partial\,\overline{v'^2}}{\partial y}\right)\right) dM \qquad (15)$$

$$C(A_Z, K_Z) = -\int_M \left(\frac{R}{P}\right)(\bar{\omega} - \{\bar{\omega}\})\,(T - \{\overline{T}\}]\, dM \qquad (16)$$

$$C(A_S, K_S) = -\int_M \left(\frac{R}{P}\right)[\,\bar{\omega}^*\ \overline{T}^*]\, dM \qquad (17)$$

Fig. 2 plots the integrands of the above equations.

3.3. *Frictional dissipation of kinetic energy*

In addition to energy terms, their fluxes and their conversion terms, the dissipation of kinetic energy is also required in order to discuss the energy flow diagram. A rough estimate is made here of this term :

$$D = \int_{1000}^{100} \underset{\sim}{V} \cdot \underset{\sim}{F}\, \frac{dp}{g} \qquad (18)$$

The frictional force $\underset{\sim}{F}$ can be expressed in terms of the wind stresses $\underset{\sim}{\tau}$ as follows :

$$\underset{\sim}{F} = -g\ \frac{\partial \underset{\sim}{\tau}}{\partial p} \qquad (19)$$

Within the planetary boundary layer, upto 900 mb the wind stress over land is computed using the relation

$$\tilde{\tau}_0 = C_D \rho_0 \, V_0 \tilde{V}_0 \qquad (20)$$

where C_D is the drag coefficient. C_D is here assumed to be 2.5×10^{-3} over the land region and over the oceanic region, the empirical formula

$$C_D = 5.1 \times 10^{-4} V^{0.46} \qquad (21)$$

is used to evaluate the drag coefficient (Garratt 1977).

For the layer 1000-900 mb, we rewrite Eqn. (18,) as:

$$D_{1000-900} = \tilde{V} . (\tilde{\tau}_{1000} - \tilde{\tau}_{900}) \qquad (22)$$

The term $(\tilde{V} . \tilde{\tau}_{900})$ is small compared to $(\tilde{V} . \tilde{\tau}_{1000})$ (less than 10% according to Holopainen (1963) and hence Eqn. (22) can be written as

$$D_{1000-900} \approx \tilde{V} . \tilde{\tau}_{1000}$$

$$\text{or} \qquad D_{1000-900} \approx C_D \, \rho_0 \, u_0^3 + C_D \, \rho_0 \, v_0^3$$

where ρ_0 is the density of air, u_0 and v_0 are the u and v components of wind at the surface.

For the layer above the planetary boundary layer. the wind stress is computed from Eqn. (23) assuming a constant eddy viscosity, having a value 1.0 x 10^5 cm^2 sec^{-1} (Holopainen 1962)

$$\tilde{\tau} = - k \, g \, \rho^2 \, \frac{\partial \tilde{V}}{\partial p} \qquad (23)$$

Expression for dissipation for the layer 900-100 mb is obtained from Eqns. (18), (19) and (23) (Gilman 1964)

$$D_{900-100} = - \int_{900}^{100} \rho^2 \, k \, g^2 \left(\left(\frac{2}{\rho} \, \frac{\partial \rho}{\partial p} \, \frac{\partial u}{\partial p} + \frac{\partial^2 u}{\partial p^2} \right) u + \right.$$

$$\left. + \left(\frac{2}{\rho} \, \frac{\partial \rho}{\partial p} \, \frac{\partial v}{\partial p} + \frac{\partial^2 v}{\partial p^2} \right) \, v \right) \frac{dp}{g} \qquad (24)$$

In order to facilitate the computation of dissipations of zonal, standing eddy and transient eddy kinetic energy separately a simplification has been introduced by assuming $\tilde{F}$ to be time invariant.

$$i.e., \qquad \tilde{F} = \bar{\tilde{F}}$$

with this assumption, the values of the dissipation terms particularly that of transient eddy would be underestimated. Hence the estimate of frictional dissipation is rather approximate. Table 2 gives the dissipation of kinetic energy at different layers.

TABLE 2

Dissipation of kinetic energy (Units : J m^{-2} s^{-1} or Watt m^{-2})

Term	1000–850mb	850–700mb	700–500mb	500–300mb	300–100mb	1000–100mb
$D(K_Z)$	0.02	0.49	0.03	0.39	0.38	1.31
$D(K_S)$	0.05	0.62	0.28	0.34	0.17	1.46
$D(K_T)$	—	1.10	0.07	0.05	—	1.22

4. Discussion of results

4.1. *Energy terms*

The values of energy terms obtained here are given below :

A_{Z_b} : the barotropic contribution to zonal A.P.E. $= 1833$ kj m^{-2}

A_{Z_c} : the baroclinic contribution to zonal A.P.E. $= 154$ k j m^{-2}

A_S : the standing eddy A.P.E. $= 136$ k j m^{-2}

A_T : the transient eddy A.P.E. $= 255$ k j m^{-2}

K_Z : the zonal K.E. $= 277$ kj m^{-2}

K_S : the standing eddy K.E. $= 61$ k j m^{-2}

K_T : the transient eddy K.E. $= 141$ k j m^{-2}

Although, the total zonal available potential energy is one order higher than zonal kinetic energy, the baroclinic contribution to the available potential energy is of the same order of magnitude as zonal kinetic energy.

Figs. 1(a–c) depict the vertical cross-sections of zonal, standing eddy and transient eddy available potential energy. Zonal available potential energy here and in subsequent discussions means A_{Z_c} defined above. From Figs. 1(a) and 1(b), it is clearly seen that there is more energy in the region between 10° N and 35° N with two maxima at 850 mb and 300 mb. As the warmest region is between latitudes 30° N to 35° N, at this region and to the south, the north-south temperature variance is large, and consequently zonal available potential energy is also more. In the case of standing eddy available potential energy the east-west temperature variance is caused by the warm regions over Iran, Arabia etc compared to the cool northeast India. It is interesting to note that this is the region of monsoon trough as also of the formation and movement of the monsoon system. Fig. 1(c) suggests that the maximum value of transient eddy available potential energy is at 300 mb around 37.5° N. The figure does not show significantly high values over the region of monsoon trough or around 15-20° N latitudinal belt where most of the depressions form and move. This is possibly because there is no significant temperature gradient in the field of monsoon depression and other transient systems.

The vertical cross sections of zonal, standing eddy and transient eddy kinetic energy are given in Figs. 1(d)–1(f). From Fig.1(d), the existence of easterly jet around 10–15°N, the subtropical jet of northern hemisphere near 40°N and that of southern hemisphere near 20° S is clear. In the lower troposphere there are two maxima, one between 10° N and 20° N and the other between 10° S and 20° S. Fig. 1(e) suggests that in the upper troposphere over 15° N and also over 15° S there are high values of standing eddy kinetic energy. In lower troposphere also, the higher values are seen in the region of seasonal trough. Fig. 1(f) shows a region of significantly high values around 20° S at 300 mb. It is difficult to explain this, but it may be mentioned that possibly the temporal changes of the westerly jet of the southern hemisphere cause such high values. This figure also shows rather high values over the region around 30° N at 300 mb and over the region around 20° N at 700 mb where the extratropical systems in the westerlies and the monsoon depressions respectively move.

From Table 1, it can be inferred that in cases of all energy terms excepting transient eddy A.P.E. and zonal kinetic energy, there has been influx of energy when the entire region is considered. There is an outflow of a small amount 2.6×10^{-2} J $m^{-2}s^{-1}$ of kinetic energy and inflow of 27.8×10^{-2} J $m^{-2}s^{-1}$ of available potential enrgy. Hence the net gain of energy is 25.2×10^{-2} J m^{-2} s^{-1} or 0.25 W m^{-2}.

4.2. *Conversion terms*

Figs. 2(a–c) represent the vertical cross-section of conversion rate of available potential energy between the zonal current and the standing eddy between the zonal current and the transient eddy and between the two types of eddies. The conversions are due to meridional transport of heat.

These figures plot the integrands of the expressions for energy conversion terms. Fig. 2(a) suggests that in most parts to the north of 10°N, there has been conversion from zonal current to standing eddy. There are two maxima — one at 850 mb level near 22.5° N and the other at 100 mb near 27.5° N, suggesting gain of available potential energy by the standing eddy or the semi-permanent systems in those regions. The monsoon trough is situated between 20° and 26° N and therefore, it could be inferred that the monsoon trough gains available potential energy from the zonal current (from north-south temperature variance). There is a small region at 300 mb near 35° N where zonal current gains from the standing eddy. For the layer 1000–100 mb in the area under study, there is a conversion of 257×10^{-2} J $m^{-2}s^{-1}$ of zonal available potential energy into the standing eddy available potential energy.

If we consider the region north of 5° N in Fig. 2(b), it is seen that between 700 mb and 400 mb levels generally, the transient eddies lose available potential energy to zonal current, but when the entire troposphere is considered, transient eddy gains 42.3×10^{-2} J $m^{-2}s^{-1}$ from zonal current. Fig. 2(c) shows the conversion rates are rather small. In general north of 10° N upto 30° N the transient eddy loses available potential energy to standing eddy, although further north of 30° N the transient eddy gains. There has been a conversion of available potential energy from transient eddy to standing eddy by a small amount (2.2×10^{-2} J $m^{-2}s^{-1}$) when the entire region is considered.

Figs. 2 (d–f) plot the vertical crosss-sections of the conversion rates of kinetic energy among the various systems. This is essentially accomplished by the meridional transport of u-momentum. Fig. 2 (d) shows between 1000 mb and 500 mb, over the region between 10° N and 30°N zonal kinetic energy is converted into standing eddy kinetic energy. In the remaining region above 500 mb north of 5° N, the standing eddy kinetic energy is converted into zonal kinetic energy with a maximum conversion near 30° N at 100 mb. In the entire region, there is a conversion of 18.3×10^{-2}J$m^{-2}s^{-1}$ from standing eddy kinetic energy to zonal kinetic energy.

From Fig. 2(e), it is clear that between 12.5° N and 30°N, from 850 to 500 mb level, transient eddy gains kinetic energy from zonal current; north of 30° N and south of 10° N conversion is generally reversed. In the entire region, zonal current loses kinetic energy to transient eddy by a small amount of 0.3×10^{-2} J$m^{-2}s^{-1}$. Fig. 2 (f) shows the conversion rates between the eddies. From 850 to 500 mb over the area between 15° N and 25° N, standing eddy gains kinetic energy from transient eddy. In other words, the monsoon trough gains energy from monsoon depression. This explains the commonly observed feature that when the monsoon activity is weak or when there is a break in the monsoon activity, reactivation of the monsoon takes place with the formation of a depression in the Bay of Bengal, or the passage of a depression/low from Indo-China area into the Bay of Bengal. Another region of maximum conversion rate is at 300 mb where the ridges and troughs of westerlies prevail. When the entire region is considered, transient eddy gains 2.8×10^{-2} J$m^{-2}s^{-1}$ of kinetic energy from standing eddy.

The available potential energy is converted into kinetic energy when the warm air rises and /or cold air sinks and kinetic energy is converted into available potential energy when the warm air sinks and/or the cold air rises due to dynamical or orographical forcings. Figs. 2 (g & h) depict the vertical cross-sections of these conversions. Fig. 2(g) shows that north of the equator, zonal available potential energy is converted into zonal kinetic energy, except over region between 20° N and 30° N from 850 mb to 600 mb level. Fig. 2(h) shows that standing eddy available potential energy is converted into standing eddy kinetic energy north of equator except from 850 to 700 mb level over the region between 10° N and 30° N. It is interesting to note that in the region of monsoon trough and the associated cyclonic circulation, kinetic energy is converted into available potential energy in both the cases of zonal current and standing eddy. Possibly dynamical forcings have forced the rising of cold air or the sinking of warm air or both. This is obvious in the case of standing eddy as there is upward motion over cooler northeast India compared to downward motion over the warmer regions of Iran, Iraq and Arabia as can be seen from the vertical velocity field in Part I of this paper (Rajamani 1985). Keshavamurti and Awade (1970) have obtained similar results. When we consider entire region, we see that 17.6×10^{-2} J$m^{-2}s^{-1}$ available potential energy is converted into kinetic energy in the case of zonal current and 21.1×10^{-2} J $m^{-2}s^{-1}$ in the case of standing eddy.

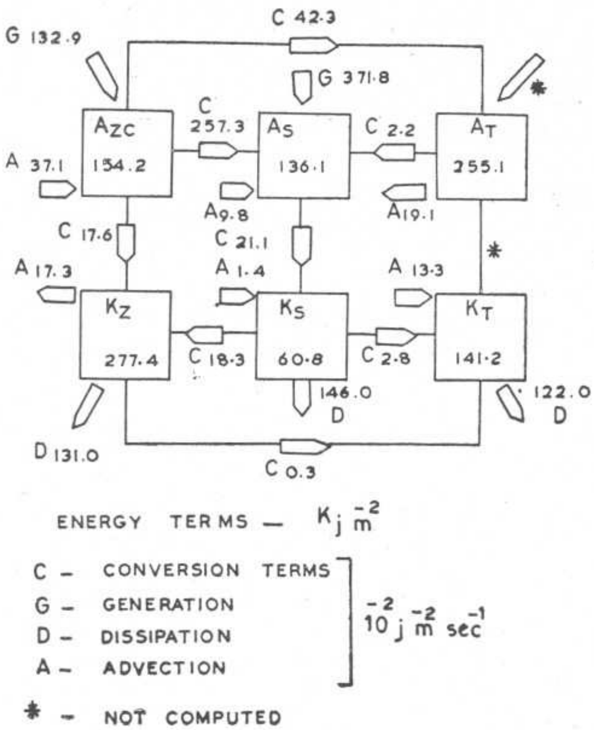


Fig. 3. Energy flow diagram (Energy terms : k J m^{-2}, other terms : 10^{-2} J m^{-2} s^{-1})

4.3. *Energy flow diagram*

Fig. 3 represents the energy flow diagram for the layer 1000-100 mb over the area from 5° N to 35° N and from 35° E to 115° E. The values obtained in this study are comparable with those obtained by Newell *et al.* (1974) for the northern hemisphere for the season June to August. The flow diagram suggests generation of both zonal and standing eddy available potential energy (computed in Part I), their magnitudes being 1.3 J m^{-2} s^{-1} and 3.7 J m^{-2} s^{-1} respectively. Zonal current is the source of available potential energy for both standing eddy and transient eddy. Standing eddy has also gained available potential energy from transient eddy but has been the source of kinetic energy for zonal current as well as for the transient eddy. This feature is consistent with the belief that the semi-permanent systems supply energy to transient eddies in addition to their contribution to the maintenance of the zonal current. Available potential energy is converted into kinetic energy in both cases of zonal current and standing eddy.

Dissipation of kinetic energy is roughly estimated to be about 4 $Jm^{-2}s^{-1}$ (W m^{-2}) while the generation of available potential energy is about 5 J m^{-2} s^{-1} (Wm^{-2}). With about 0.25 J m^{-2} s^{-1} (Wm^{-2}) of energy advected into the area of interest there is a marginal excess in the energy gained compared to the energy lost due to dissipation. Added to this there could be positive generation of transient eddy available potential energy (Rao and Rajamani 1972).

5. Concluding remarks

Discussions above, lead to the following picture of the monsoon circulation. The differential heating of the Asian land mass and the Indian Ocean causes the north-south temperature variance, which is proportional to zonal available potential energy. This is the source of available potential energy to semi-permanent systems and transient systems. In addition to, a part of it is directly converted into kinetic energy of the zonal current. The diabatic heating generates standing eddy available potential energy. This is converted into standing eddy kinetic energy. The semi-permanent systems which are formed due to the orography of the region are the sources of kinetic energy for transient systems as well as for the zonal current.

Over the region of monsoon trough between 17.5°N and 27.5° N from surface to 500 mb level, the semi-permanent system gains kinetic energy both from zonal current and from transient systems. The latter feature suggests the importance of depressions in strengthening of the monsoon trough and in increasing the monsoon activity. The transient systems gain kinetic energy from zonal current, however, the amount is small.

In this study, the frictional dissipation of kinetic energy and the advection of both available potential energy and kinetic energy estimated are rather very approximate and the generation of transient eddy available potential energy has not been computed. Hence the energy balance of the monsoon circulation is not attempted here. However, the study brings out the direction of energy transformation, *i.e.*, the interactions between the various monsoon systems and the order of magnitude of the dissipation of kinetic energy, the generation of available potential energy and the advection of both.

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References

Garratt, J.R., 1977, Review of drag coefficients over oceans and continents, *Mon. Weath. Rev.*, **105**, 915-929.

Gilman, P.A., 1964, On the vertical transport of angular momentum in the atmosphere, *Pure & Appl. Geophys.*, **54**, 161-166.

Holopainen, E.O., 1962, Some empirical stress values for the lower troposphere, *Geophysics*, **8**, 151-158.

Holopainen, E.O., 1963, On the dissipation of kinetic energy in atmosphere, *Tellus*, **15**, 26-32.

Holopainen, E.O., 1970, An observational study of the energy balance of the stationary disturbances in the atmosphere, *Quart. J. R. Met. Soc.*, **96**, 626-644.

Keshavamurti, R.N. and Awade, S.T., 1970, On the maintenance of the mean monsoon trough over north India, *Mon. Weath. Rev.*, **98**, 315-319.

Krishnamurti, T.N., Kanamitsu, M., Godbole, R., Chang, C.B., Carr, R. and Chow, J.H., 1976, Study of a monsoon depression: II—Dynamical structure, *J. Met. Soc. Japan*, **54**, 208-225.

Lorenz, E. N., 1955, Available potential energy and the maintenance of the general circulation, *Tellus*, **7**, 157-167.

Lorenz, E.N., 1967, The nature and theory of general circulation of atmosphere, Geneva, WMO, 1-161.

Murakami, T., 1960, On the maintenance of kinetic energy of the large scale stationary disturbances in the atmosphere, Sci. Rep. No. 2, Planetary circulation Project, Dept. of Meteorology, M.I.T., 42.

Murakami, T., 1963, Maintenance of the kinetic energy of the disturbances appearing on the monthly mean weather charts, *J. Met. Soc. Japan*, **41**, 15-28.

Newell, R.E., Vincent, D.G., Dopplick, T.G., Ferruza, D. and Kidson, J.W., 1970, The energy balance of the global atmosphere in '*The general circulation of the atmosphere*', G.A. Corby, ed. London, R. Met. Soc, 42-90.

Newell, R.E., Kidson, J.W., Vincent, D.G. and Boer, G.J., 1974, *The Genetal circulation of the tropical atmosphere and interactions with extratropical latitudes*, **2**, Cambridge, Mass. MIT. Press.

Oort, A.H., 1964, On estimates of the atmospheric energy cycles, *Mon. Weath. Rev.*, **92**, 483-493.

Rajamani, S., 1985, Energetics of the monsoon circulation over south Asia,—Part I : Diabatic heating and the generation of available potential energy, *Mausam*, **36**, 1.

Rao, K.V. and Rajamani, S., 1972, Study of heat sources and sinks and the generation of available potential energy in the Indian region during the southwest monsoon, *Mon. Weath. Rev.*, **100**, 383-388.

Smith, P.J., 1969, On the contribution of limited region to the global energy budget, *Tellus*, **21**, 202-207.

Vincent, D.G. and Chang, L.N., 1973, Some further considerations concerning energy budgets of moving systems, *Tellus*, **25**, 224-232.

Appendix

A — Total available potential energy

A_Z — Zonal available potential energy

A_S — Standing eddy available potential energy

A_T — Transient eddy available potential energy

K_Z — Zonal kinetic energy

K_S — Standing eddy kinetic energy

K_T — Transient eddy kinetic energy

M — Mass of the atmosphere over the area under study

σ — Static stability

R — Gas constant

P — Pressure in mb

T — Temperature

u — x-component of wind vector (eastward)

v — y - component of wind vector (northward)

ω — vertical component of wind ($\frac{dp}{dt}$) in isobaric co-ordinates.

$\underset{\sim}{V}$ — Wind vector.

Q — Rate of heating.

g — Acceleration due to gravity.

c_p —Specific heat at contant pressure.

f — Coriolis parameter.

ζ — Relative vorticity.

η — Absolute vorticity.

$\underset{\sim}{k}$ — Unit vector in the vertical.

k — Eddy viscosity.

$\underset{\sim}{\tau}$ — Wind stress vector.

C_D —Drag coefficient.

dL — Increment in length.

L — Length enveloping the area under study.

θ — Potential temperature.

α — Specific volume

$\underset{\sim}{F}$ — Friction

D — Dissipation.

ρ — Density of air.

($\frown$) —Hemispherical mean.

($^{-}$)—Time mean (mean of July 1963).

$$[x] \text{ — Zonal mean of } x = \frac{1}{\int_{35^\circ E}^{115^\circ E} d\lambda} \int_{35^\circ E}^{115^\circ E} x \, d\lambda$$

$\{x\}$— Mean of x over the area under study.

$$= \frac{1}{\int_{5^\circ N}^{35^\circ N} \int_{35^\circ E}^{115^\circ E} a^2 \cos\phi \, d\lambda \, d\phi} \int_{5^\circ N}^{35^\circ N} \int_{35^\circ E}^{115^\circ E} x a^2 \cos\phi \, d\lambda \, d\phi$$

($''$) — Deviation from hemispherical mean.

($'$) — Deviation from time mean.

(*)— Deviation from zonal mean.