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On some energy aspects of the monsoon depression during its life cycle

S. RAJAMANI and J. R. KULKARNI

Indian Institute of Tropical Meteorology, Pune

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सार— 1 से 10 जुलाई तक की अवधि के लिये सापेक्ष भ्रमिलता, ऊर्जा पदों, ऊर्जा रूपान्तरण पदों तथा संवेग व ताप के स्थानान्तरण का अभिकलन किया गया था। ऊर्जा विनिमय का अध्ययन करने के लिये इसमें मानसून अवदाब का जीवन चक्र आ जाता है यह ऊर्जा विनिमय अवदाब के प्रबल होने व कमजोर पड़ने की अवधि के दौरान मानसून परिसंचरण के विभिन्न अवयवों तथा संवेग तथा ताप के स्थानान्तरण के बीच होता है।

रुचिकर बात है कि इस अवधि में एक ही समय में एक साथ दो अवदाब थे, एक बंगाल की खाड़ी के ऊपर तथा दूसरा अरब सागर के ऊपर। इस अभिकलन संबंधी अध्ययन से यह अनुमान लगाया गया कि बंगाल की खाड़ी के ऊपर वाला अवदाब निम्न क्षोभमण्डल में स्पष्ट रूप से सभी स्तरों पर एक साथ बन गया जबकि अरब सागर वाला अवदाब पहले 700 मि० बार की ऊंचाई पर बना तथा बाद में धरातल पर उतरा। क्षेत्रीय तथा भंवरीय गतिज ऊर्जा तथा क्षेत्रीय उपलब्ध स्थित ऊर्जा दोनों ही अवदाबों के प्रबल होने से बढ़ा किन्तु उपलब्ध भंवरीय स्थित ऊर्जा में कोई व्यवस्थित परिवर्तन नहीं आया। साथ ही इस अवधि में समस्त क्षोभमण्डल में संवेग का उत्तर दिशा में स्थानान्तरण तथा निचले क्षोभमण्डल में दक्षिण दिशा की ओर ताप का स्थानान्तरण बढ़ गया सामान्यतया भंवरों ने क्षेत्रीय धाराओं से उपलब्ध स्थित ऊर्जा प्राप्त की जबकि क्षेत्रीय धाराओं ने निचले स्तर पर गतिज ऊर्जा प्राप्त की तथा उच्च स्तर पर छोड़ दी।

ABSTRACT. Relative vorticity, energy terms, energy conversion terms and the transports of momentum and heat were computed for the period from 1 to 10 July 1973, which covered the life cycle of a monsoon depression in order to study the energy exchange between the different components of the monsoon circulation and the transports of momentum and heat during strengthening and decaying period of the depression.

Interestingly, there were two depressions, one over the Bay of Bengal and the other over the Arabian Sea co-existing during this period. From this computational study it is inferred that whereas the system over the Bay of Bengal apparently formed simultaneously at all levels in the lower troposphere, the second system formed first at a higher level around 700 mb and then descended to the surface. Both zonal and eddy kinetic energy as well as the zonal available potential energy increased with the strengthening of the systems but there is no systematic change in the eddy available potential energy. Also, during this period the northward transport of the momentum in the entire troposphere and the southward transport of heat in the lower troposphere increased. In general, the eddies gained available potential energy from the zonal current whereas the zonal current gained kinetic energy in the lower levels and lost it in the higher levels.

1. Introduction

Monsoon depression is one of the important components of the summer monsoon circulation over South Asia. During the monsoon period on an average about 3 depressions form in a month over the north Bay of Bengal. Sometimes the reminiscents of the systems formed in the western Pacific Ocean reach the north Bay of Bengal after crossing Indo-China area and these weakened systems revive and strengthen into depression/deep depression while over the sea. These systems rarely reach the intensity of hurricanes as they are over the sea for short time. However, they cause copious rainfall along their tracks. Also they revive the monsoon activity when weak monsoon activity or break condition prevails. They move in a westward or northwestward direction. In the latter half of the monsoon season if they reach around 25 deg. N latitude they recurve and move northeastwards or eastwards.

Over Gujarat region (northwest India) adjacent to the Arabian Sea, depressions form which are most intense at higher levels rather than at the surface (Miller and Keshavamurti 1968). The maximum values of vorticity are around 700 mb level. These systems, known as mid-tropospheric cyclones (MTC) are rather quasi-stationary. Sometimes the low pressure systems from the Bay of Bengal on reaching this region acquire the characteristics of MTC. Krishnamurti *et al.* (1975, 1976), Daggupathy and Sikka (1977), Sikka (1979),

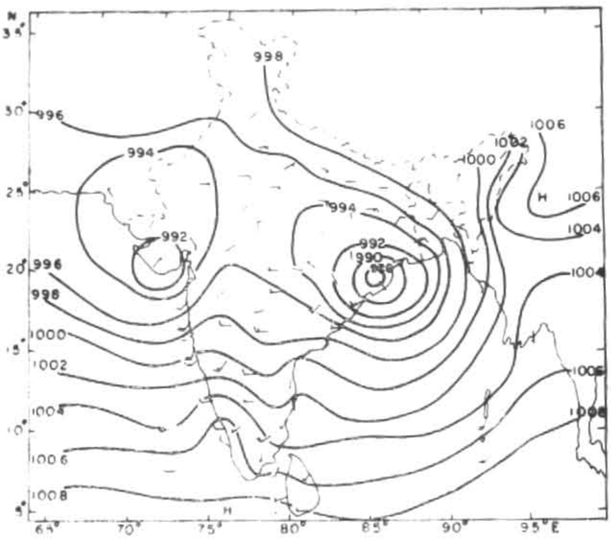


Fig. 1. Synoptic situation on 7 July 1973 at 0300 GMT

Rao *et al.* (1978), Godbole (1975 and others have recently made studies on various aspects of the monsoon depression. Mak (1975) and Carr (1977) have examined theoretical aspects of the mid-tropospheric cyclones. In the present study, in order to examine the energy exchanges between the various components of the monsoon circulation and the transports of momentum and heat during the life cycle of a monsoon depression, the relative vorticity, the energy terms, the energy conversion terms and the transports of momentum and heat etc have been computed daily for a period from 1 to 10 July 1973. During this period a monsoon depression formed over the Bay of Bengal (System I), strengthened into a deep depression, moving west-northwards, crossed the coast, weakened and then finally merged with the seasonal trough. Also, another system (System II) over northeast Arabian Sea formed during this period. As the Indo-Soviet Monsoon Experiment (ISMEX-73) was carried out from 16 May to 11 July 1973 radiosonde data from Russian ships and Indian ships were available over the Arabian Sea which otherwise is generally a data sparse region.

2. Synoptic situation and data

The period from 1 July to 10 July 1973 was chosen in order to include a few days before the formation of the depression. The System I formed as a low on 4 July 1973 at the head Bay of Bengal. It intensified into a depression with centre at 19.5 deg. N. 88 deg. E on 5 July and further intensified into deep depression on 6 July with the centre at 19.5 deg. N and 86.5 deg. E. On this day simultaneously another low (System II) formed over Gujarat-Saurashtra region (21 deg. N, 71 deg. E approximately). These two systems coexisted for a few days and caused good rainfall over most parts of the country. The two systems strengthened and reached maximum intensity on 7 and 8 July. On 9 July 'System I' weakened into a depression and on 10 July it merged with seasonal monsoon trough. The System II weakened into a low on 9 July and on the next day moved to the region, Sind (23 deg. N, 67 deg. E approximately), but continued as a low pressure area. During this period, the System I moved from 90 deg. E to 80 deg. E while the System II remained nearly stationary. The synoptic situation for 7 July, when the two systems reached their maximum intensity is given in Fig. 1.

Using all available data, including the data from Indian and USSR research ships over the Arabian Sea, analyses of the wind and temperature fields were carefully made by an experienced analyst, at all standard levels, *viz*., 1000, 850, 700, 500, 300 and 200 mb levels for the period 1 to 10 July 1973. A flat bottom surface was assumed over the Himalayan region and the analyses at 1000, 850, 700 mb levels were extended over this region also, considering observations from stations around. From the streamline, isotach and temperature analyses, wind direction, wind speed and temperature were picked up at the grid points of 2 deg. Lat./Long. interval over the area from 2 deg. to 40 deg. N and from 50 deg. to 110 deg. E.

3. Computations

The relative vorticity was computed using the wind field. The available potential energy, kinetic energy, the energy conversion terms and the transports of momentum and heat were also calculated from the available data.

The expressions for zonal and eddy available potential energy as given by Lorenz (1955) are

$$A_Z = \int_M \frac{1}{2\widetilde{\sigma}}\left(\frac{R}{P}\right)^2 \left([T] - \widetilde{T}\right)^2 dM \qquad (1)$$

$$A_E = \int_M \frac{1}{2\widetilde{\sigma}}\left(\frac{R}{P}\right)^2 \left(T - [T]\right)^2 dM \qquad (2)$$

where $\widetilde{\sigma} = -\widetilde{\alpha}\frac{\partial}{\partial P}\ln\widetilde{\theta}$, is the static stability parameter, $\widetilde{\alpha} = \frac{RT}{P}$, $\widetilde{\theta}$ is the global mean potential temperature, $\widetilde{T}$ is the global mean temperature and M is the mass of the atmosphere and [ ] denotes the latitudinal average. The zonal available potential energy can be split into barotropic contribution and baroclinic contribution when the energetics

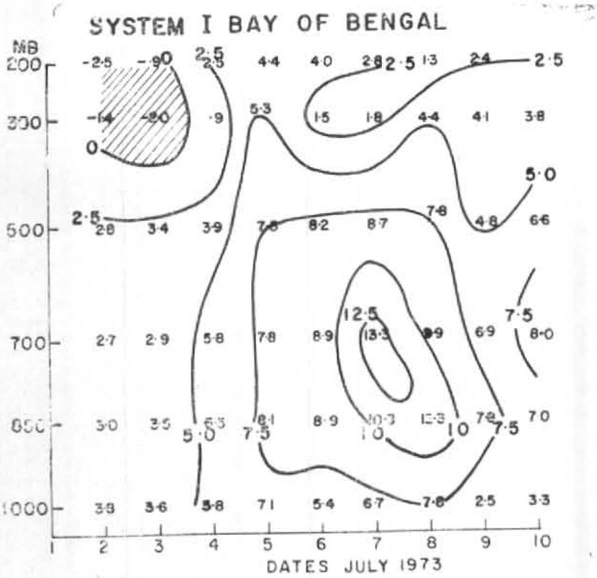


Fig. 2(a). Vertical time section of maximum relative vorticity around the centre of the depression ($10^{-5}s^{-1}$)

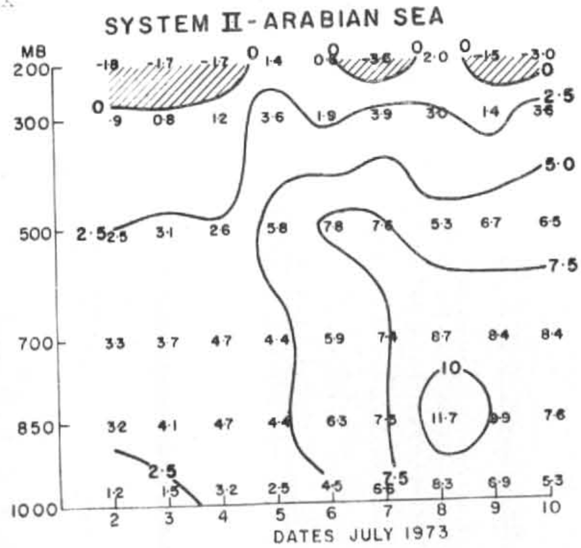


Fig. 2(b). Vertical time section of maximum relative vorticity around the centre of the depression ($10^{-5}s^{-1}$)

of a limited region having atmosphere of mass M_j, is considered (Smith 1969 Vincent and Chang 1973), *i.e.*, Eqn. (1) can be written as :

$$A_Z = \int_{M_j} \frac{1}{2\widetilde{\sigma}} \left(\frac{R}{P}\right)^2 \left([T] - \{T\}\right)^2 dM_j + $$

$$+ \int_{M_j} \frac{1}{2\widetilde{\sigma}} \left(\frac{R}{P}\right)^2 \left(\{T\} - \widetilde{T}\right)^2 dM_j$$

$$A_Z = A_{zc} + A_{zb}$$

A_{zc} and A_{zb} are the baroclinic and barotropic contributions of the limited region to the global zonal available potential energy.

$$A_{zb} = \int_{M_j} \frac{1}{2\widetilde{\sigma}} \left(\frac{R}{P}\right)^2 \left(\{T\} - \widetilde{T}\right)^2 dM_j \qquad (1a)$$

$$A_{zc} = \int_{M_j} \frac{1}{2\widetilde{\sigma}} \left(\frac{R}{P}\right)^2 \left([T] - \{T\}\right)^2 dM_j \qquad (1b)$$

where $\{T\}$ is the area mean temperature over the given limited region. The expression for the kinetic energy is given by :

$$K_Z = \int_{M_j} \frac{1}{2} \left([u]^2 + [v]^2\right) dM_j \qquad (3)$$

$$K_E = \int_{M_j} \frac{1}{2} \left([u^{*2}] + [v^{*2}]\right) dM_j \qquad (4)$$

where, $u^* = u - [u]$ and $v^* = v - [v]$.

The energy conversion terms were computed from the following expressions (Lorenz 1955, Oort 1964 and Newell *et al.* 1974) :

$$C(A_Z, A_E) = -\int_{M_j} \frac{1}{\widetilde{\sigma}} \left(\frac{R}{P}\right)^2 \left[v^* T^*\right] \frac{\partial [T]}{\partial y}\, dM_j \qquad (5)$$

$$C(K_Z, A_E) = -\int_{M_j} \left[u^* v^*\right] \frac{\partial [u]}{\partial y}\, dM_j \qquad (6)$$

4. Discussion of results

4.1. *Relative vorticity*

The patterns of relative vorticity over the regions of System I and System II were examined separately. For this, the maximum relative vorticity values in the regions of the two systems were picked up separately at each of all the standard levels for the period from 2 to 10 July 1973 and the vertical sections were prepared (Figs. 2a and 2b). From Fig. 2(a) it can be seen that even before the formation of the depression over Bay of Bengal (System I) the values of maximum relative vorticity at 1000 mb on 2 and 3 July 1973 were positive and high. The high positive values before the formation of the System I were because of the monsoon trough in that region. The maximum value of vorticity decreased with height becoming negative at 300 mb and 200 mb levels. The values of maximum relative vorticity increased after 4 July at all levels and the value was highest on 7 July at 700 mb level indicating that the system reached maximum intensity on that day. In contrast to this, in the case of the depression over Arabian Sea, the maximum relative vorticity was at 700 mb on 2 July and at 850 mb on 3 July. After 4 July the maximum relative vorticity was high at 1000 mb also. It may be inferred that whereas the System I simultaneously formed in the lower troposphere, System II, possibly formed first at

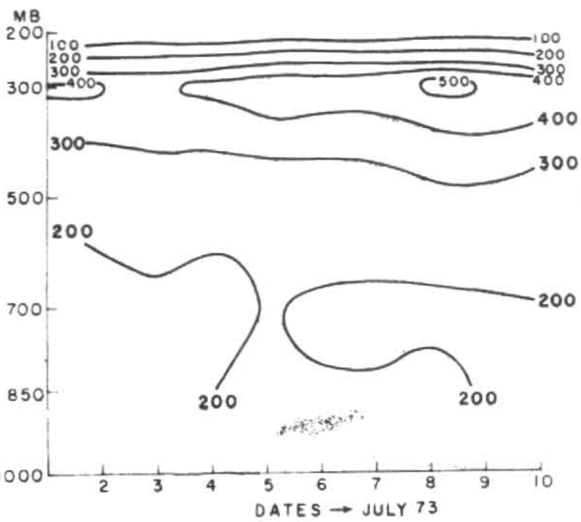


Fig. 3(a). Vertical time section barotropic part of available potential energy ($m^2. s^{-2}$)

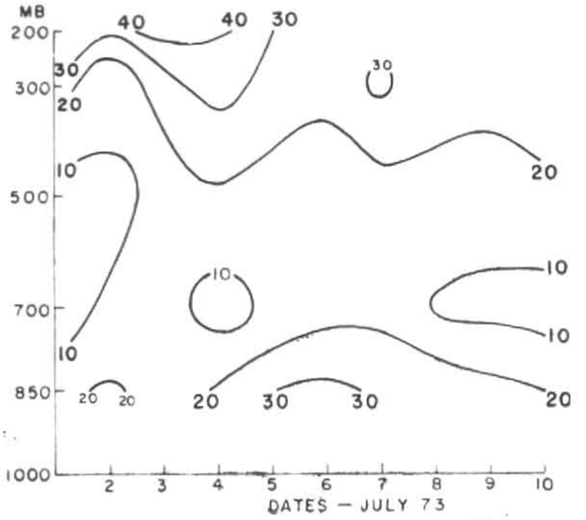


Fig. 3(b). Vertical time section of baroclinic part of available potential energy ($m^2. s^{-2}$)

850/700 mb levels, before the system descended to 1000 mb level. The highest value of relative vorticity in the case of the System II was on 8 July at 850 mb level.

4.2. *Available potential energy*

Barotropic part (A_{zb}) and baroclinic part (A_{zc}) of zonal available potential energy and the eddy available potential energy were computed from Eqns. 1(a), 1(b) and (2) respectively. The vertical time section of the barotropic part of available potential energy, A_{zb} (Fig. 3a) shows that from 5 July onwards when the system has intensified into a depression, there is a sudden increase in the values with a maximum on 8 July. Also, this figure shows the values are higher at 500 and 300 mb levels on all days, but at 200 mb level the values are very much less.

Since A_{zb} is proportional to $(\{T\} - \widetilde{T})^2$, *i.e.*, the square of the difference in the space average over the region of interest and the hemispherical average of the temperature (Actually, $\widetilde{T}$, the hemispherical average of monthly mean temperature is used. Higher values of A_{zb} on the days, when the system was present would mean warmer "area mean temperatures", $\{T\}$ over the region of our interest, possibly due to more convective activity. As the maximum diabatic heating takes place in the upper troposphere around 400 mb level (Reed and Recker 1971 and Rajamani 1978), A_{zb} is more at 300 mb level particularly on the active depression days when the convective activity has been more. The maximum value on 8 July at almost all levels may be due to the most intense rainfall activity on 7 July 1973.

The baroclinic part of zonal available potential energy, A_{zc} or the zonal available potential energy of the limited region (Vincent and Chang 1973) is depicted in Fig. 3 (b). It can be seen from this figure that the values at 850 mb level are higher on 5, 6 and 7 July. At 200 and 300 mb levels, the maximum value was on 3 July and 4 July respectively prior to the formation of the System I. At 700 and 500 mb levels, the values are less than those at 850 and 300 levels. However, there is an increasing trend in A_{zc} in lower troposphere when

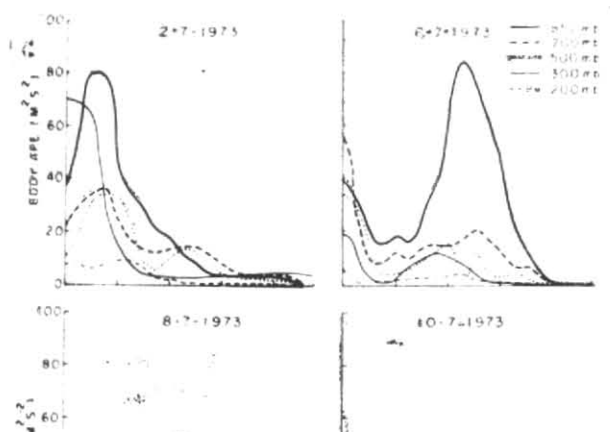


Fig. 3(c). Latitudinal variation of eddy available potential energy at different isobaric levels on different dates ($m^2. s^{-2}$)

this system intensified. The values of eddy available potential energy (not shown in figure) did not change in any systematic way with the intensification of the System I and System II. This is possibly because there is no variation of temperature across the system. This is in contrast to the extra tropical system where the temperature contrast across the system is rather marked in matured stage.

Fig. 3(c) shows the variation of eddy available potential energy along the latitudes of various levels on 2, 6, 8, 10 July representing pre-formation, formation, mature and dissipation stages of the depression. The values at 850 mb level on formative, mature and dissipation stages and at 300 mb on pre-formation stage are higher than at other levels. It also can be seen that at 850 mb level, prior to the formation of the system, the region of

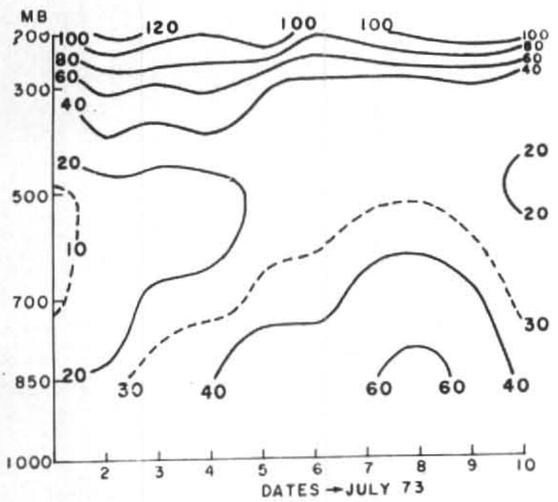


Fig. 4(a). Vertical time section of zonal kinetic energy ($m^2.s^{-2}$)

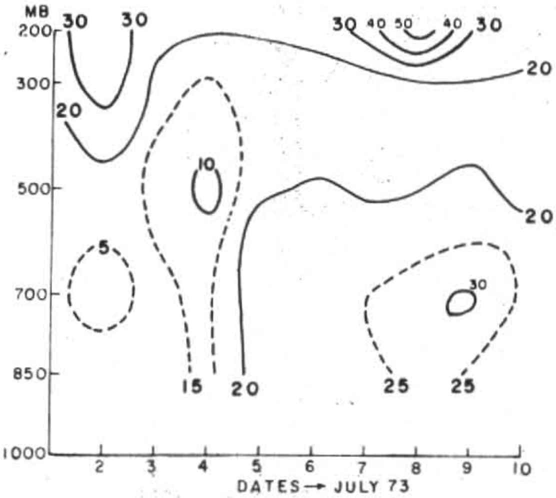


Fig. 4(b). Vertical time section of eddy kinetic energy ($m^2.s^{-2}$)

maximum value correspond to 36°-40° N, but afterwards the region of maximum value is at 20° N or so where the system was present.

4.3. *Kinetic energy*

Fig. 4(a) depicts the vertical time section of zonal kinetic energy computed from Eqn. (3). The high values at 300 mb and 200 mb levels are due to the westerly jet, north of 30° N and the easterly jet around 10° N. At 850 mb comparatively high values of K_Z are due to the strong southwesterly wind prevailing south of 20° N. At this level the values increase after the formation of the depression, reach maximum on 8 July (Fig. 4a). This brings out the feature that when the monsoon depression strengthens, the monsoon circulation or the basic current also strengthens. Although the values at 200 mb level remain almost constant, those at 300 mb decrease after the formation of the depression. At 500 mb and below the values of K_Z increase after the formation of the system.

There is easterly thermal wind over the monsoon region because of the warmer temperature in north and colder temperature in the south. This causes westerlies to decrease with height, to become variable wind around 500 mb level and further higher levels to become easterlies. The low values of K_Z at 500 mb are because of this reason.

Fig. 4(b) depicts the vertical cross section of eddy kinetic energy computed from Eqn. (4). At lower levels, the values of K_E increase after the formation of the system on 4 July, reaching maximum on 9 July and then decrease.

At 200 mb level, there are higher values a few days prior to the formation of the depression and again on 8 July when the system had reached the maximum intensity.

4.4. *Transport of momentum*

Fig. 5(c) shows the vertical section of the transport of momentum at different latitudes for 2 July a few days prior to the formation of the monsoon depression and for 8 July when it was fully established. The rate of transport has been higher when the depression had strengthened. On 2 July there has been northward transport of momentum between 14° & 24° N in the region of the seasonal monsoon trough. On 8 July, the depression was around 20° N. North of this position there is southward transport of momentum and south of this position there is northward transport of momentum with maximum transport at 700 mb level so that there has been convergence of the momentum around 20° N. This has caused an increase in kinetic energy of the eddies on 9 July. However, it may be remembered that on 9 July the vorticity decreased compared to the previous day. At 200 mb the northward transport of momentum increased in general north of 16° N. South of 16° N the the transport is in an opposite direction resulting in the divergence of momentum around 16° N.

Fig. 5(a) shows the vertical time section of the momentum transport from 1 to 10 July. It is easily seen from this figure that until 7 July, generally there is northward transport at lower troposphere and southward transport in upper troposphere. On 8, 9, 10 July the transport in the entire troposphere from 850 mb to to 200 mb is northward. Except at 850 mb level at all other levels there is a trend of increasing in the northward transport of momentum with the growth of the system.

Fig. 5(d) shows the vertical section of transport of heat for different latitudes for 2 and 8 July. There has been southward transport of heat in the region of the monsoon trough on both days. On 2 July at 300 mb around 34° N there is maximum northward transport, whereas on 8 July the northward transport is over much less region. The vertical time section (Fig. 5b) shows that on all days at lower levels (850 and 700 mb) the transport is southward with maximum values at 850 mb on 8-10 July when the system reached maximum intensity. At higher levels, it is northward and the maximum transport prior to the formation of depression.

4.5. *Conversion terms*

The conversion rates between the zonal available potential energy and the eddy available potential energy

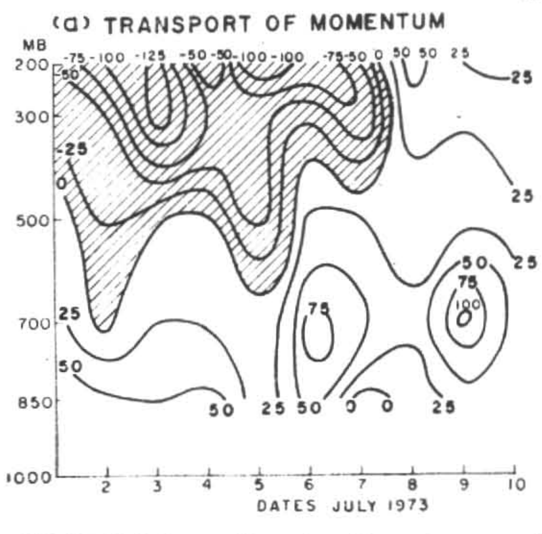


Fig. 5(a). Vertical time section of meridional transport of momentum ($m^2. s^{-2}$)

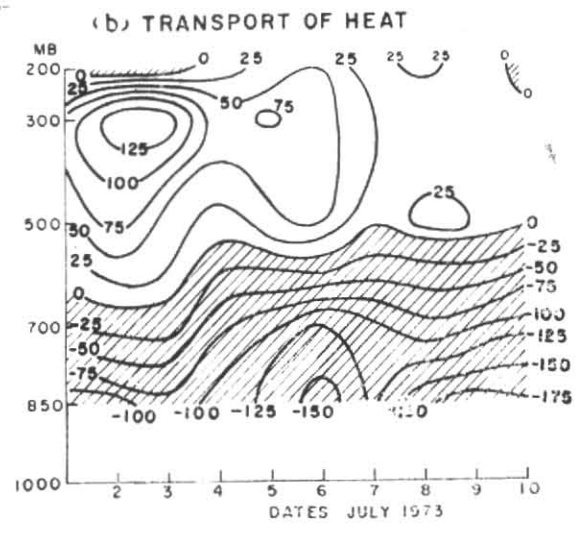
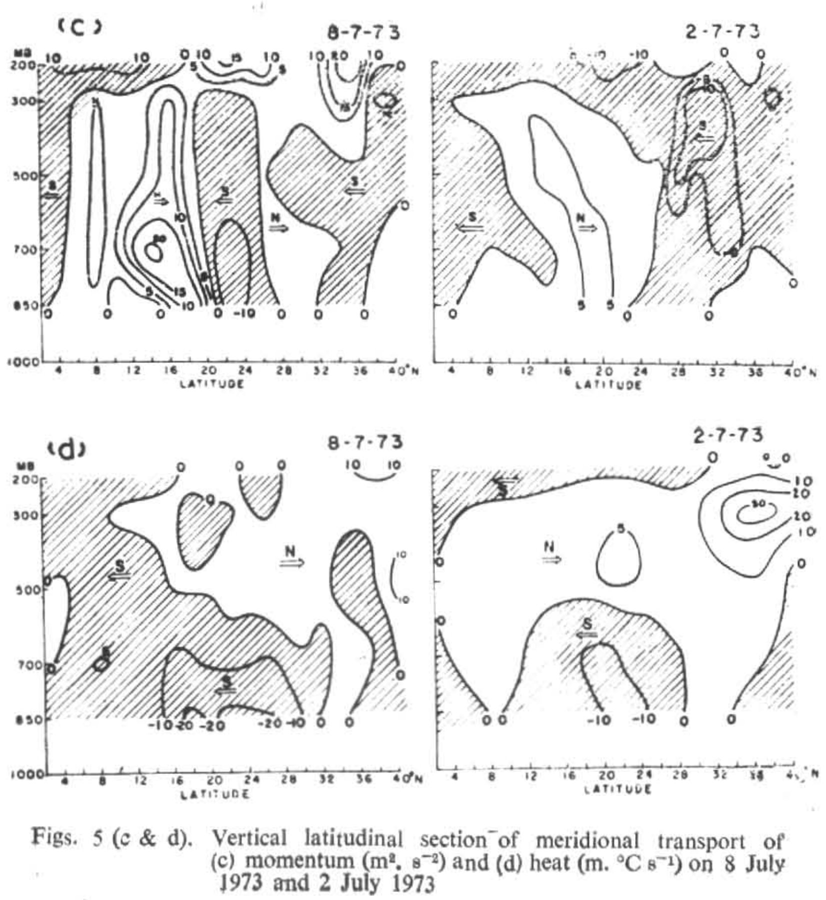


Fig. 5(b). Vertical time section of meridional transport of heat (m. °C s^{-1})



Figs. 5 (c & d). Vertical latitudinal section of meridional transport of (c) momentum ($m^2. s^{-2}$) and (d) heat (m. °C s^{-1}) on 8 July 1973 and 2 July 1973

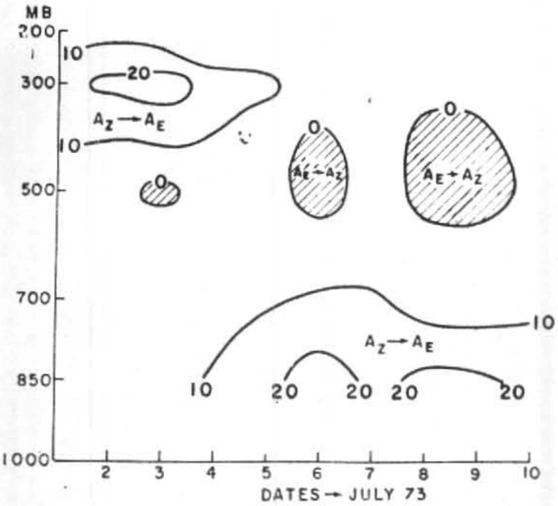


Fig. 6(a). Vertical time section of conversion of available potential energy from zonal current to eddies ($m^2.\ s^{-3}$)

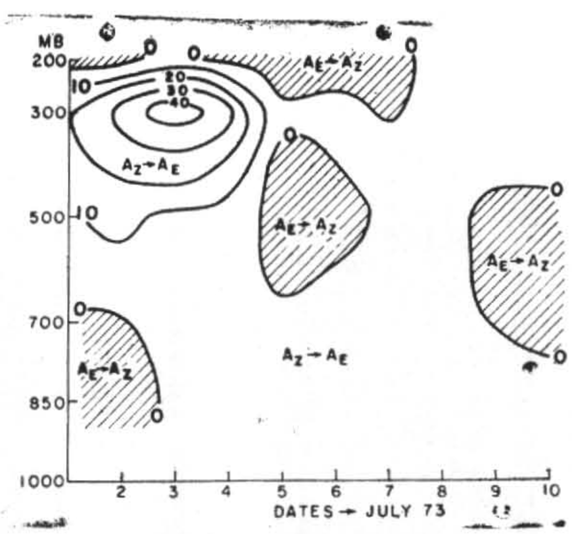


Fig. 6(b). Same as in Fig. 6(a) for smaller region from 78° to 111° E– Bay of Bengal ($m^2.\ s^{-3}$)

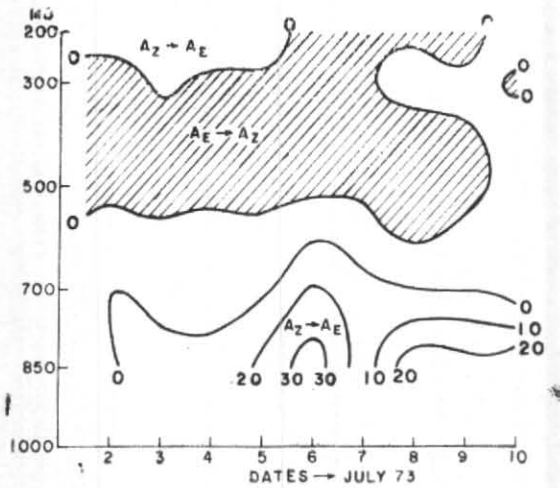


Fig. 6(c). Same as in Fig. 6 (a) for smaller region from 50° to 76° E—Arabian Sea ($m^2.\ s^{-3}$)

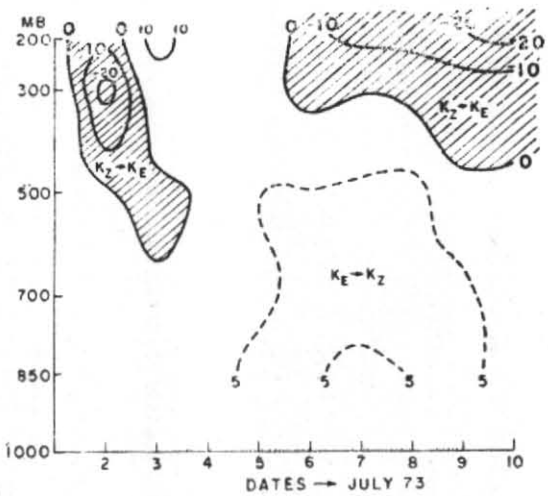


Fig. 6(d). Vertical time section of conversion of kinetic energy from eddies to zonal current ($m^2.\ s^{-3}$)

were computed from Eqn. (5). Actually the conversion is between the baroclinic part of zonal available potential energy, A_{z_c} and the eddy available potential energy, A_E. Fig. 6(a) shows the conversion rates for the entire region and Figs. 6(b) and 6(c) for the smaller region which contain the System I over Bay of Bengal and System II over the Arabian Sea respectively. It is seen from Fig. 6(a) that predominantly the conversion is from zonal current to the eddy with the first maximum at 300 mb level on 2/3 July, a few days prior to the formation of System I. Comparing with Fig. 6(b) this region of maximum at 300 mb level is due to the System I. Other maximum conversions are at 850 mb on 6 and 8 July when the two systems have become deep depressions. The maximum conversion is due to the System II over Gujarat-Saurashtra region as can be seen by comparing Figs. 6(a) with 6 (c). Due to System I the conversion of available potential energy from zonal currents to eddy is more in upper troposphere particularly at 300 mb (Fig. 6b). But, due to the System II the conversion is from zonal current to eddy in lower troposphere and from eddy to zonal current in upper troposphere.

Fig. 6(d) depicts the conversion of kinetic energy from zonal current to eddy and *vice versa.* This shows the conversion is from eddy to zonal current in lower troposphere on all days with maximum conversion on 7 July when the system was most intense. Although the eddy is giving energy to zonal current it also has been intensifying upto 7/8 July. This may be possible if the conversion of A_E eddy available potential energy into eddy kinetic energy is in substantial amounts. However, at upper troposphere at 300 and 200 mb eddy has gained kinetic energy from zonal current during intensifying period of the depression.

5. Concluding remarks

The study suggests the following features from vorticity patterns. It seems that the System I over the head Bay, has formed simultaneously at all levels in the lower troposphere whereas the System II over Gujarat Saurashtra border, has formed at 850/700 mb level first before descending to surface. From the computations made in this study, the following observations could be made : The barotropic part of zonal available potential energy increased when the system formed and intensified possibly because of the convective activity over the monsoon region, this region has warmed up as compared to global mean temperature. Although the baroclinic part of the zonal available potential energy increased slightly when the Systems I and II strengthened, there is no systematic change in eddy available potential energy during this period. Both zonal and eddy kinetic energy increased with the strengthening of the systems which is in agreement with the well known feature that when the monsoon depression intensifies, the monsoon circulation as a whole strengthens.

When the systems are active there is northward transport of momentum in the entire troposphere. The southward transport of heat increased in the lower troposphere whereas the northward transport of heat in the upper troposphere decreased, as the system intensified. In general the eddies gain available potential energy from the zonal current. The zonal current gains kinetic energy from the eddies/monsoon systems in lower levels whereas in the upper levels like 300 mb and 200 mb eddies gain kinetic energy.

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