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On the role of large scale energetics in the onset and maintenance of summer monsoon — I : Heat budget

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सार – उष्णकटिबंधीय पट्टी (20° द. – 40° उ. एवं 0° पू. - 150° पू.) में दक्षिण-पश्चिम एशिया मानसून की गतिविधियों एवं शुरुआत पर बृहतमानी उष्मा बजट के प्रभाव का अध्ययन किया गया है : इसके अध्ययन के लिए मई-जुलाई 1979 में किए गये प्रथम भूमंडलीय वायुमंडल अनुसंधान कार्यक्रम (जी ए आर पी) के अन्तर्गत भूमंडलीय प्रयोग (एफ जी जी ई) के III बी स्तर विश्लेषण का उपयोग किया गया है ।

मानसून की गतिविधियों पर उष्मा बजट समीकरण की विभिन्न पदों के विचरण, ऊर्ध्वाधर वितरण और आवधित माध्य के प्रभाव को ज्ञात करने के लिए उनका काफी बरीकी से परीक्षण किया गया है । जिससे पता चलता है कि केरल के तट पर मानसून के शुरू होने के लगभग 2 सप्ताह पूर्व पूर्ण उष्मा का क्षैतिज अभिसरण और डाइबैटिक उश्मन में महत्वपूर्ण वृधि हुई और 16 जुलाई 1979 को भारत में शुरु होने वाले मानसून व्यवधान के लगभग एक सप्ताह पहले भी इन मानों में ह्रास की प्रवृति देखी गई । ऊर्ध्वाधर बंटन, आवधिक माध्य और परीसीमा अभिवाह से भी उपरोक्त निष्कर्षों की पुष्टि होती है ।

ABSTRACT. The effect of large scale heat budget on the onset and activities of southwest Asian monsoon is studied for the tropical belt (20 deg. S-40 deg. N and 0 deg. E-150 deg. E). For this study the level-IIIb analysis of the First GARP Global Experiment (FGGE) during May-July 1979 is utilised.

The daily variation, vertical distribution and period averages of the various terms in heat budget equation are closely examined to find out their influence on the activities of monsoon. It is found that there is significant increase in the net enthalpy, horizontal convergence of heat and diabatic heating about two weeks before the onset of monsoon over Kerala coast. It is further found that a decreasing trend in these values is observed about one week before the break monsoon condition, which started over India on 16 July 1979. The vertical distribution, period averages and the boundary fluxes also confirm the above findings.

1. Introduction

The Asian summer monsoon is established in late May or in early June in a spectacular manner and persists roughly for a period of four months. Though the southwest monsoon is a regional phenomenon and very much seasonal in nature, it plays significant role in the atmospheric general circulation. Moreover, now it is widely recognised that a better understanding of the monsoon circulation needs certain distinctly different circulation patterns outside the monsoon region which may be closely associated with this system.

The onset of southwest monsoon over Indian sub-continent is one of the important aspects in the evaluation of the regional summer monsoon system. Though, there is no precise and unique definition of the term 'Onset of monsoon', in general, the Indian meteorologists determine the date of onset of monsoon over Kerala coast on the basis of 'a sharp increase and characteristic persistency in the rainfall over the southwest coast of India' (Ananthakrishnan *et al.* 1968). Thus, the rainfall amount, which is the mainly used criterion, is the end product of a series of large scale processes which cause significant changes in the patterns of motion, heat and moisture contents, cloudiness and so on of the atmosphere well in advance. Further, with the commencement of the monsoon, the remarkable increase of rainfall over Indian sub-continent

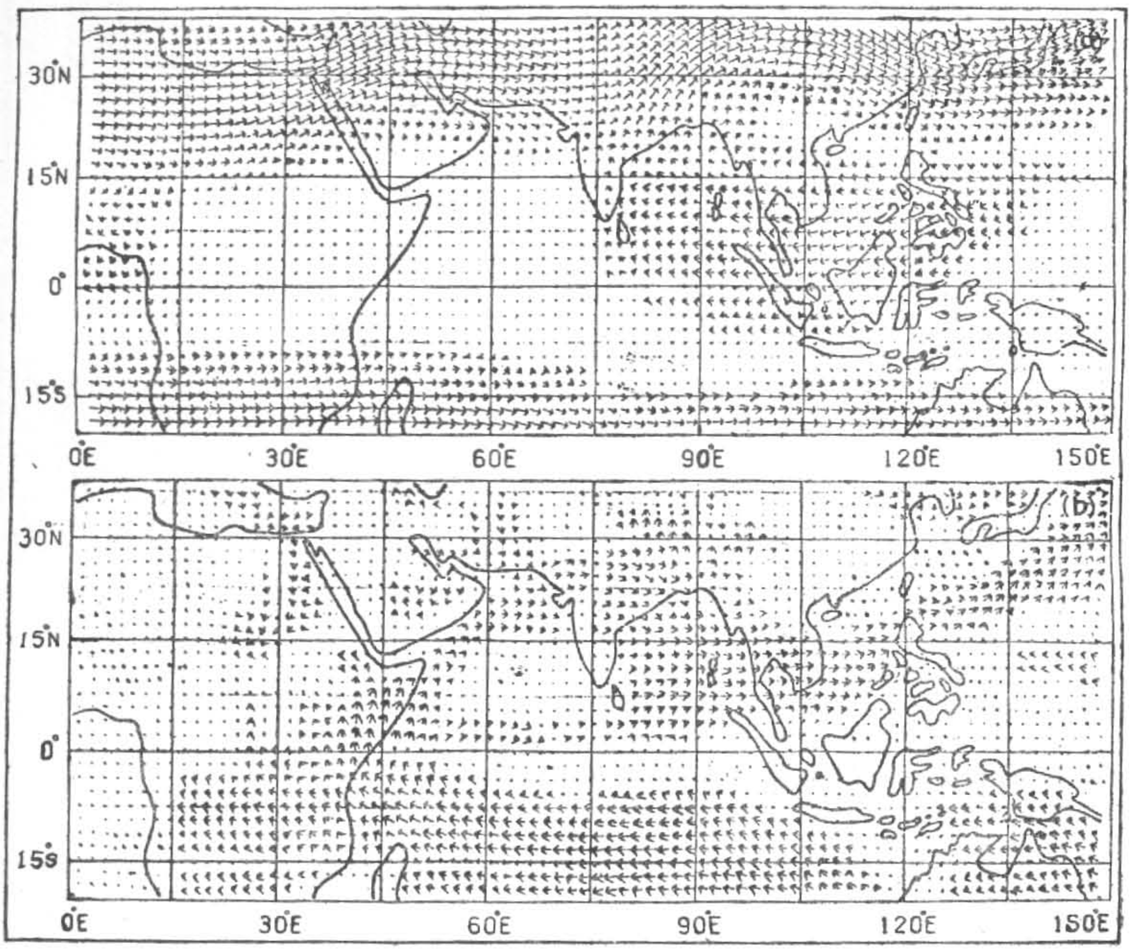

Fig. 1. Observed mean wind field for the period 16-31 May 1979 at (a) 150 mb and (b) 850 mb

and change in the circulation pattern of the troposphere influence the large scale heat and moisture budget to a great extent (Newell *et al.* 1974). Therefore, a detailed study of the heat and moisture budget over a large monsoon area is crucial in understanding the physical mechanism of the onset and maintenance of southwest monsoon.

The GARP Summer Monsoon Experiment during FGGE year represents a milestone in the development of monsoon meteorology. For the first time a truly tropical belt data set has been provided over the data sparse oceanic region as well as, the most complete set of atmospheric data over monsoon region ever obtained. Thus, MONEX-79 provided a unique data base for numerical, as well as, diagnostic studies on summer monsoon.

There has been a significant amount of work accumulated in the area of the diagnostic study of atmospheric energetics as compiled by Newell *et al.* (1974), Oort (1964) and Wiin-Nielsen (1968). These works have revealed important basic information on hemispheric/global scale processes. A large number of study on heat and moisture budget have also been made for limited regions (Kung and Siegel 1979, Murty 1976, Savijarvi 1980, Yanai *et al.* 1973, Hantel and Hacker 1981, etc). However, most of these are confined to North America and Europe where a dense network of observations are available and some of the studies are related to the special experiments over Atlantic and Pacific such as GATE, AMTEX, etc.

A few number of work in the area of diagnostic studies related to Asian summer monsoon are found in the literature (Anjaneyulu 1969, 1971; Saha and Bavadekar 1973; Keshavamurthy 1968; Rao and Rajamani 1972; Chowdhury and Karunakar 1981 etc). Most of these studies are either limited to small region, case study or based on sparse data sets.

In the present paper an attempt has been made to study the heat budget over a large monsoon area with the help of complete data sets obtained during FGGE. The effect of heat budget on the

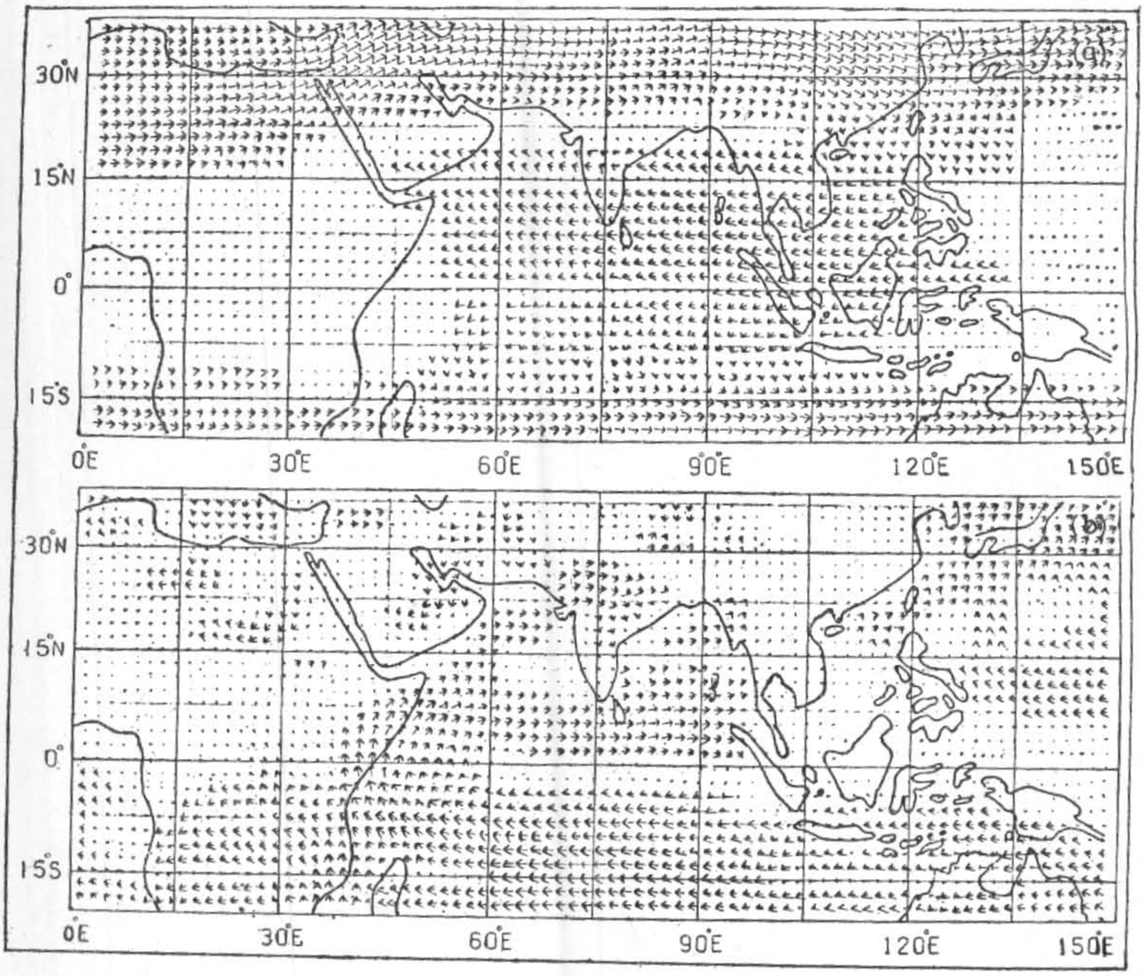

Fig. 2. Observed mean wind field for the period 1-15 June 1979 at (a) 150 mb and (b) 850 mb

onset, maintenance and break monsoon has been studied by utilising the twice daily analysis for a period of two months (May-July 1979) which cover all these events related to summer monsoon.

2. The budget equation

In pressure coordinates the heat energy (total potential energy) budget equation in the flux form can be written as :

$$\frac{\partial (c_pT)}{\partial t} + \nabla \cdot (c_pT\mathbf{V}) + \frac{\partial}{\partial p}(c_pT\omega) - \omega\alpha = Q_H \quad (1)$$

where, Q_H is the net effect of all diabatic contributions consisting mainly of radiative effects, Q_R; latent heat released, Q_L, due to net effect of condensation and evaporation and turbulent heating, Q_T. The remaining terms of the equation have their usual meaning.

The results at each regular latitude-longitude grid points are averaged horizontally over a large area, which helps to smooth out random errors, and integrated vertically from 1000-100 mb layer. Thus, the volume integration of a dummy variable X for the region bounded by meridians λ_1 and λ_2, latitude circles ϕ_1 and ϕ_2 and isobaric surfaces p_1 and p_2 may be written as :

$$\overline{X} = \frac{1}{g}\int_{\phi_1}^{\phi_2}\int_{\lambda_1}^{\lambda_2}\int_{p_1}^{p_2} X\, a^2 \cos\phi \, d\phi \, d\lambda \, dp \quad (2)$$

where a is the averaged radius of the earth.

The volume integration of the Eqn. (1), with the boundary conditions that ω vanishes at the bottom and top of the atmosphere (no flux condition), leads to the following space averaged budget equation :

$$\partial\, (\overline{c_pT}) \;/\; \partial t + \overline{\nabla \cdot (\, c_pT\mathbf{V}\,)} - \overline{\omega\alpha} = \overline{Q_H} \quad (3)$$

i.e., $S + \text{DIV} + \text{ACON} = Q$

where,

S = rate of change of enthalpy with time, *i.e.,* storage of total potential energy.

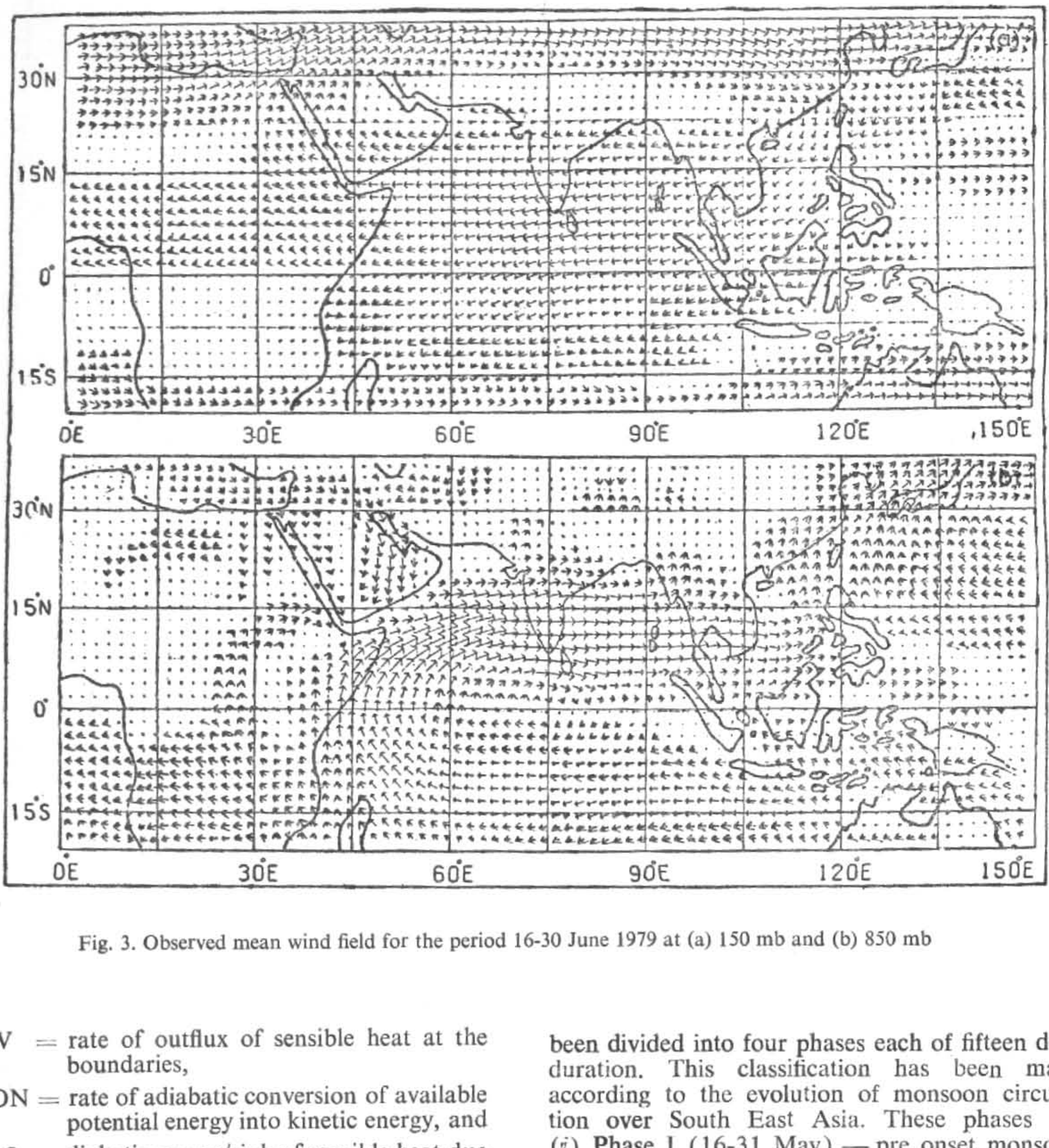

Fig. 3. Observed mean wind field for the period 16-30 June 1979 at (a) 150 mb and (b) 850 mb

DIV = rate of outflux of sensible heat at the boundaries,

ACON = rate of adiabatic conversion of available potential energy into kinetic energy, and

Q = diabatic source/sink of sensible heat due to radiation, condensation and turbulent processes.

3. Data set and analysis procedure

The data base for this study consists of twice daily FGGE level-IIIb analysis of temperature, relative humidity, geopotential and wind fields for a tropical belt from 20 deg. S to 40 deg. N and 0 deg. E to 150 deg. E at ten pressure levels (1000, 850, 700, 500, 400, 300, 250, 200, 150, 100 mb) for the period 16 May-15 July 1979. These data records are obtained by using a four dimensional multivariate data assimilation scheme, developed and processed at the European Centre for Medium Range Weather Forecasts (ECMWF). This two months period has been divided into four phases each of fifteen days duration. This classification has been made according to the evolution of monsoon circulation over South East Asia. These phases are (*i*) Phase I (16-31 May) — pre onset monsoon period, (*ii*) Phase II (1-15 June) — onset period over Indian subcontinent, (*iii*) Phase III (16-30 June) — well established monsoon circulation over South East Asia and (*iv*) Phase IV (1-15 July) — period before the break monsoon condition over the Indian subcontinent. These four phases represent the time evolution of tropospheric flow during the summer monsoon, which are characterised by the wind fields at 850 mb and 150 mb levels. These two isobaric surfaces are quite significant as they are the representative levels for low level westerly jet over Arabian Sea and tropical easterly jet over South East Asia. Flow patterns of these levels are illustrated in Figs. 1-4 and some of their salient features are summarised in Table 1.

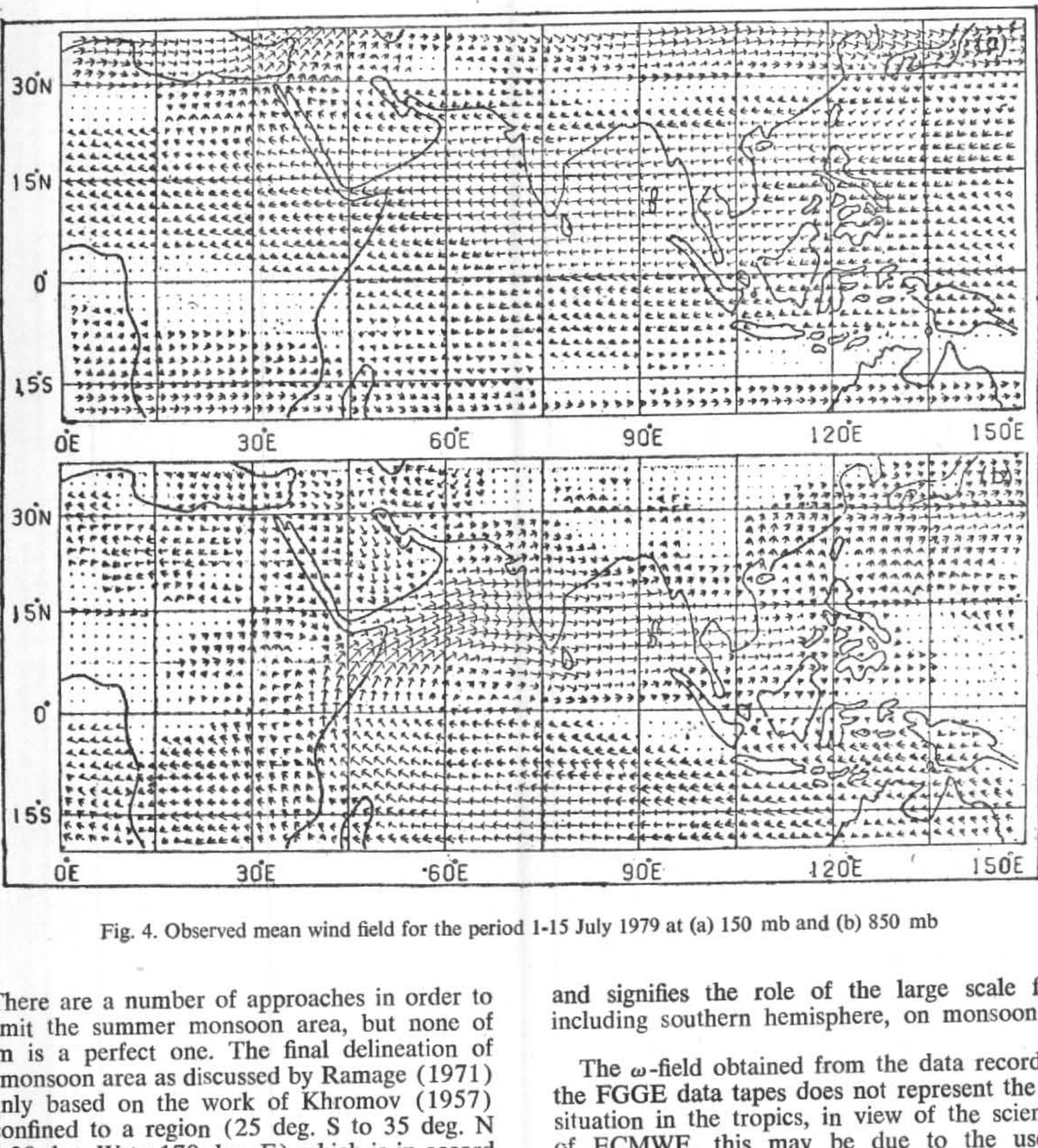

Fig. 4. Observed mean wind field for the period 1-15 July 1979 at (a) 150 mb and (b) 850 mb

There are a number of approaches in order to delimit the summer monsoon area, but none of them is a perfect one. The final delineation of the monsoon area as discussed by Ramage (1971) mainly based on the work of Khromov (1957) is confined to a region (25 deg. S to 35 deg. N and 30 deg. W to 170 deg. E) which is in accord with the region considered for this study. In view of the sparsity of the data over large oceanic area, most of the budget studies for Indian summer monsoon are confined to a limited region (Keshavamurthi 1968, Bunker 1965 etc). Oort and Chan (1977) in their study on angular momentum and kinetic energy balance over the Asian monsoon region confined the monsoon region to 1.25 deg. S to 28.75 deg. N and 2.5 deg. W to 157.5 deg. E based on the work of Sadler (1975). The longitudinal extent of this region well agrees with our region whereas the role of southern hemispheric tropical belt is better represented in our study. Further, the results obtained by horizontal average over a large area helps to smooth out the random errors and signifies the role of the large scale flow, including southern hemisphere, on monsoon.

The ω-field obtained from the data records of the FGGE data tapes does not represent the real situation in the tropics, in view of the scientists of ECMWF, this may be due to the use of normal mode initialisation technique for obtaining the initialised ω-field. This necessiates an alternative method for estimation of the ω-field from available uninitialised data records. The kinematic estimate of ω-field from the upper air wind fields is more reliable since it is based on no assumptions about the nature of the atmospheric flow except the hydrostatic relationship. By specifying ω at the top or the bottom of the atmospheric layer, its value may be computed at the remaining levels by vertically integrating the equation of continuity. In spite of its basic soundness and apparent simplicity in computation the kinematic estimate of ω has been well known for its technical difficulties arising mainly due to accumulation of bias errors contained in the

TABLE 1

Main features of monsoon flow during May-July 1979

Phases	Low level flow (850 mb)	Upper level flow (150 mb)	Jet streams
	Cross equatorial flow	*Anticyclone*	*Low level Arabian Sea Jet*
I	Weak flow (8-10 m s^{-1}) confined to 40°E-50°E.	Centred at 22°N and 105°E.	Not present
II	Persists and extends up to 60°E	Elongates in east-west direction	Do.
III	Intensifies (15-20 ms^{-1})	Extends from Red Sea to East China coast	Jet with core of max. winds 20-22 ms^{-1} lies near 10-12°N.
IV	Persists	Persists	Persists
	Arabian Sea	*Cross equatorial flow (north-south)*	*Sub-tropical westerly jet*
I	Anticyclonic flow over central and eastern part	Confined to narrow region between Sumatra and Barneo.	Present over north India
II	Anticyclonic flow disappears. Organised westerly flow over southern part	Persists	Shifts further north from India and splits due to Himalayas
III	Strong westerly to southwesterly flow covers entire region	Elongates in east-west direction (50°E-120°E)	Shifts further north and disappears from Indian region
IV	Maintained with slight decreased intensity	Weakens	Shifts further north
	Bay of Bengal		*Tropical easterly jet*
I	Weak westerly flow		Weak and confined to 5°N-10°N and 95°E-115°E.
II	Well organised monsoon flow in the southern part		Extends west
III	Persists and covers the entire Bay		Strengthens, extends westward up to 25°E and broadens in N-S direction with max. winds confined to 7°N-12°N, 60°E-90°E.
IV	Persists		Persists
	Other features		
I	(*i*) Weak cyclonic flow over Indo-Pakistan area (*ii*) Well marked anticyclonic flow over Saudi Arabia (*iii*) Weak trough over Burma		
II	(*i*) Persists (*ii*) Weakens (*iii*) Shifts northwest.		
III	(*i*) Persists (*ii*) Diffuses and strong northerly to northwesterly flow joins the main Arabian Sea flow (*iii*) Shifts to north India (monsoon trough)		
IV	(i) Persists (*ii*) Weakens and persists (*iii*) Persists		

computed values of divergence. A number of techniques have been developed for kinematic estimation of vertical motion (O'Brien 1970, Kung 1973, Schmidt and Johnson 1972, Falkovich 1980). In the present study a technique has been used to estimate ω profiles in such a way that the vertical integration of divergence over the entire atmosphere vanishes. This is achieved by suitable adjustments to the divergence field similar to that used by O'Brien (1970) and Falkovich (1980).

The various space derivative terms on the left hand side of the budget equation are discretised by centred finite difference scheme while Leap-Frog method has been used to compute time derivative terms. The budget terms are estimated at each regular latitude longitude grid points and then integrated over the whole atmosphere as already mentioned in section 2 above. The diabatic source or sink of heat is estimated as residue from the budget Eqn. (3). The computations were carried out on the twelve hourly

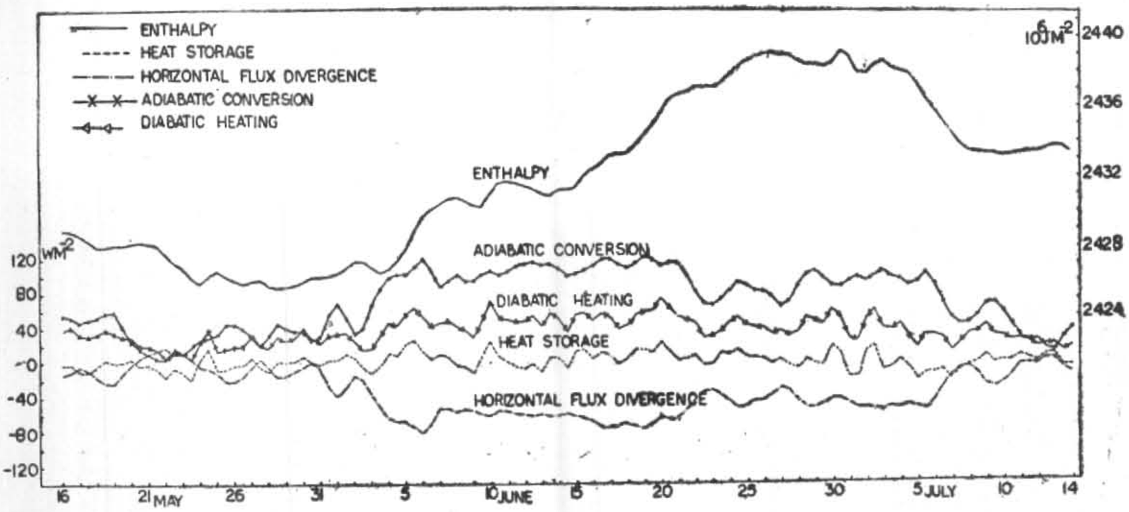

Fig. 5. Daily variation of the vertically integrated heat budget parameters

basis. The boundary fluxes are computed separately for each side of the region and intergrated vertically. The net flux across the boundaries is same as that the total horizontal divergence from the region.

4. Interpretation of results

Daily variation, vertical distribution and period averages of various terms in the heat budget equation are closely examined to find out their influence on the activities of summer monsoon over Indian subcontinent.

4.1. *Daily variation of various parameters of the heat budget equation*

Following are some of the features of daily variations of the vertically integrated enthalpy and heat budget parameters (Fig. 5) :

(1) Net enthalpy of the atmosphere decreases from 16-24 May and then ramains almost steady up to 4 June. Thereafter, a rapid and almost continuous increase is observed in enthalpy with the maximum value about 2439×10^{6} Jm^{-2} on 26 June. This value is almost maintained up to 4 July followed by a steep fall till 8 July and then remains steady up to the end of Phase IV.

Enthalpy is the measure of heat transfer during atmospheric processes. which may come through various processes such as, radiation, friction, condensation of water vapour and turbulent transfer of heat. Our results indicate an increase in the value of enthalpy from 4 June to 4 July which may be mainly attributed to the transfer of heat through condensation of water vapour and turbulent heat transfer from the surface. With the advance of monsoon these two processes are enhanced due to increase of strong latent heating in the middle troposphere through condensation and strong low level winds.

(2) There is no remarkable variation (lies between 20 and —20 Wm^{-2}) in the heat storage during all the four phases considered.

(3) During Phase I no remarkable change is observed in the values of horizontal heat flux divergence which fluctuates about zero line in the range of 20 to —20 Wm^{-2}. Significant horizontal convergence starts from 3 June. This convergence increases by about 3 to 4 times to that of the Phase I and is maintained at this high value till 6 July, thereafter it decreases rapidly.

As indicated by the low level wind patterns this horizontal convergence of heat from 3 to 6 July may be attributed to the strong low level northerly to northwesterly winds over Saudi Arabia and strong southwesterlies from warm Indian Ocean.

(4) Net adiabatic conversion ($-\omega\alpha$) of available potential energy to kinetic energy over the troposphere is positive for the entire period considered, indicating the rising motion on the average. During Phase I no remarkable change is observed in the values of net adiabatic conversion which fluctuates in the range of 10-60 Wm^{-2}. Significant increase starts from 3 June and continues up to 6 July (increases by 2-3 times that of Phase I value) and thereafter this high value is almost maintained till 6 July when it starts decreasing.

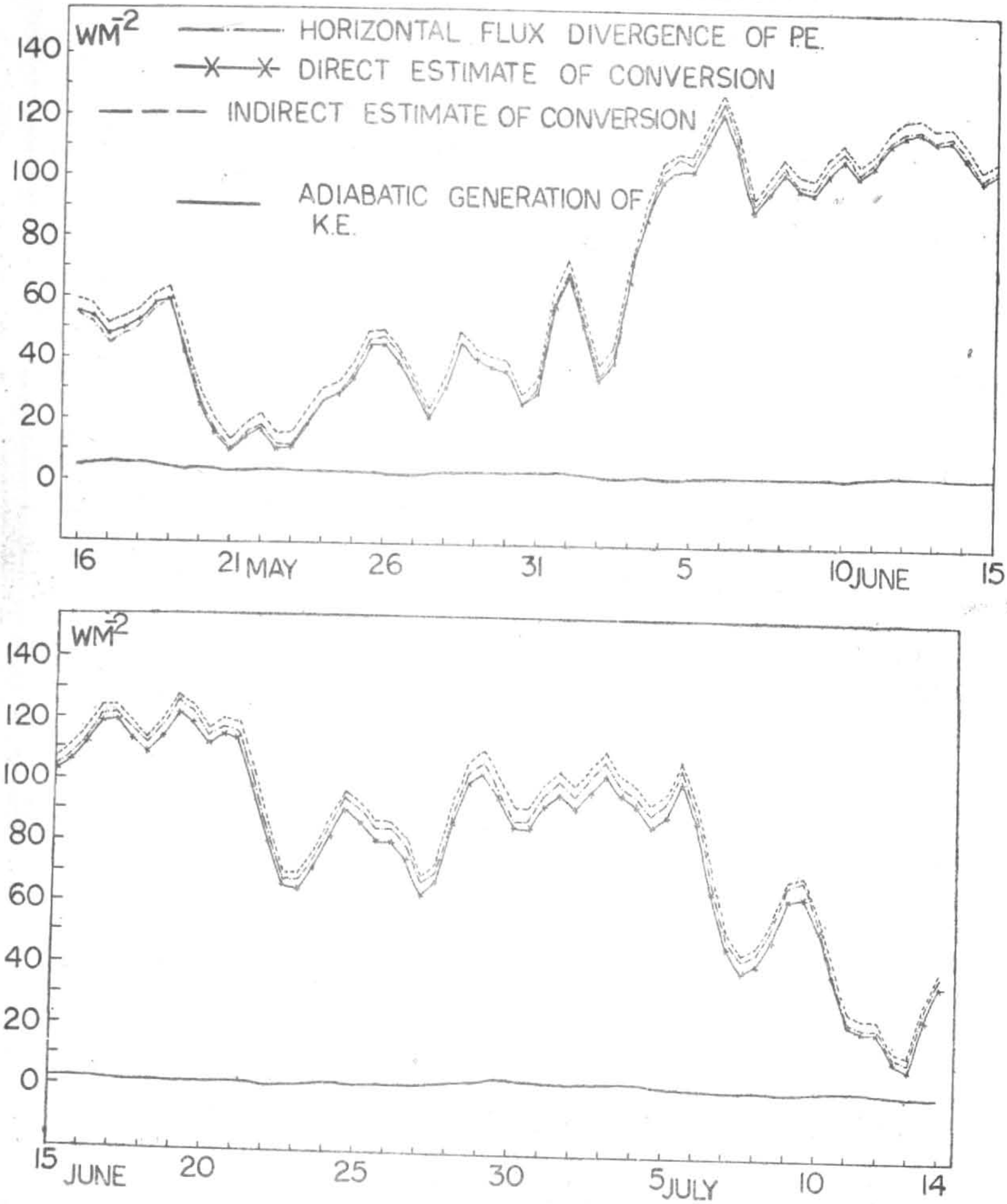

Fig. 6. Direct and indirect estimate of daily variation of the adiabatic conversion of the available potential energy to kinetic energy

The nature of daily variation of $-\omega\alpha$ during all the phases is in good agreement with the horizontal heat flux divergence in the tropics where horizontal gradient of the temperature is small, in general. This agreement leads to the fact that during active monsoon condition vertical velocity, on the average, increases considerably. A further discussion of this parameter will be made later on in this paper.

(5) For diagnosing the irreversible diabatic heating, which cannot be observed directly in the atmosphere, the residual method is adapted. In this method the diabatic terms (radiation, condensation, friction and diffusion) are estimated from the data as residuals needed to balance the heat energy budget equation. The advantage of this method is that no approximations need to be done on the nature of the diabatic processes as in the parameterisation, but on the other hand the result obtained from this gives the net effects of all the physical processes without the possibility of separating them. Further, the residue is sensitive to inaccuracies in approximating other terms and also to the observational errors. The diabatic heating is always positive over the entire period considered here. The physical mechanism causing this heating may be attributed mainly to the strong turbulent heat transfer from the relatively warm ocean and land surfaces by high low level wind speed and strong latent heating in the middle and upper troposphere through condensation of water vapour during monsoon season.

Net diabatic heating decreases from 16 to 22 May and then fluctuates between 10 and 40 Wm^{-2} up to 3 June. Thereafter, a rapid increase is observed till 6 June (65 Wm^{-2}) and then it fluctuates at higher value between 40-70 Wm^{-2} upto 22 June. From 22 June to 4 July the diabatic heating varies in the range of 25-40 Wm^{-2}. In the later part of the Phase IV the values lie between 10-40 Wm^{-2}. The diabatic heating does not indicate any clear trend as seen in the other terms of the heat budget equation, this may be due to the fact that the residual is rather more sensitive to inaccuracies in approximating the remaining terms of the equation. On the average there is considerable increase of diabatic processes during 4 June to 4 July.

4.2. *Daily variation of the adiabatic conversion of available potential energy to kinetic energy*

The kinetic energy and total potential energy budget equations are coupled by the conversion formula for the adiabatic source terms :

$$-\omega\alpha = -\mathbf{V}.\nabla\Phi + \nabla.(\Phi\mathbf{V}) + \partial(\Phi\,\omega)/\partial p$$

This links the so called conversion term $-\omega\alpha$, which may be regarded as the release of horizontal potential energy, to the kinetic energy generation $-\mathbf{V}.\nabla\Phi$ through pressure forces $\nabla.(\Phi\mathbf{V})$ and $\partial(\Phi\omega)/\partial p$ in the boundaries of the limited region. In case of a limited region these pressure forces, which are considered to be the redistribution terms for the released energy in the process of conversion from available potential energy to kinetic energy, play an important role as, the major part of the adiabatic conversion of the available potential energy is redistributed in conjunction with the generation of kinetic energy. Thus, $-\omega\alpha$ play significant role in diagnostic study of the energetics.

There are two ways of estimating $-\omega\alpha$. The first which is the direct method involves a great deal of difficulty and controversy in the computation of vertical velocity ω, the second way of estimating $-\omega\alpha$ (indirect or residual method) is to determine the right hand side terms of the above equation, which is by no means an easy task since the necessary determination of geopotential gradient in the tropics is very difficult.

Following are some of the features of daily variation of the vertically integrated adiabatic generation of kinetic energy, horizontal flux of potential energy (as net vertical flux is zero), direct and indirect estimates of adiabatic conversion (Fig. 6) :

(1) Almost there is no day to day variation in the adiabatic generation of kinetic energy throughout the period.

(2) There is net mass outflow from the region throughout the period which indicates that the region under consideration is imposing pressure force on the surrounding atmosphere through its boundaries. This parameter increases considerably during 3 June to 6 July (active monsoon period), before and after this period this horizontal flux is less by almost 50 per cent. This fact may be explained in two ways : (*i*) increase of upper level mass divergence maintains the low level heat and moisture convergence to sustain the monsoon activity, (*ii*) considerable increase of the diabatic conversion of available potential energy in the region during active monsoon period is redistributed through the lateral boundaries.

(3) The direct and indirect daily estimated adiabatic conversion remain positive and closely follow one another for the entire period and do not differ by more than 7 per cent. This close agreement of $-\omega\alpha$ determined by two methods confirm the validity of the scheme used for directly estimating the value of ω. This parameter

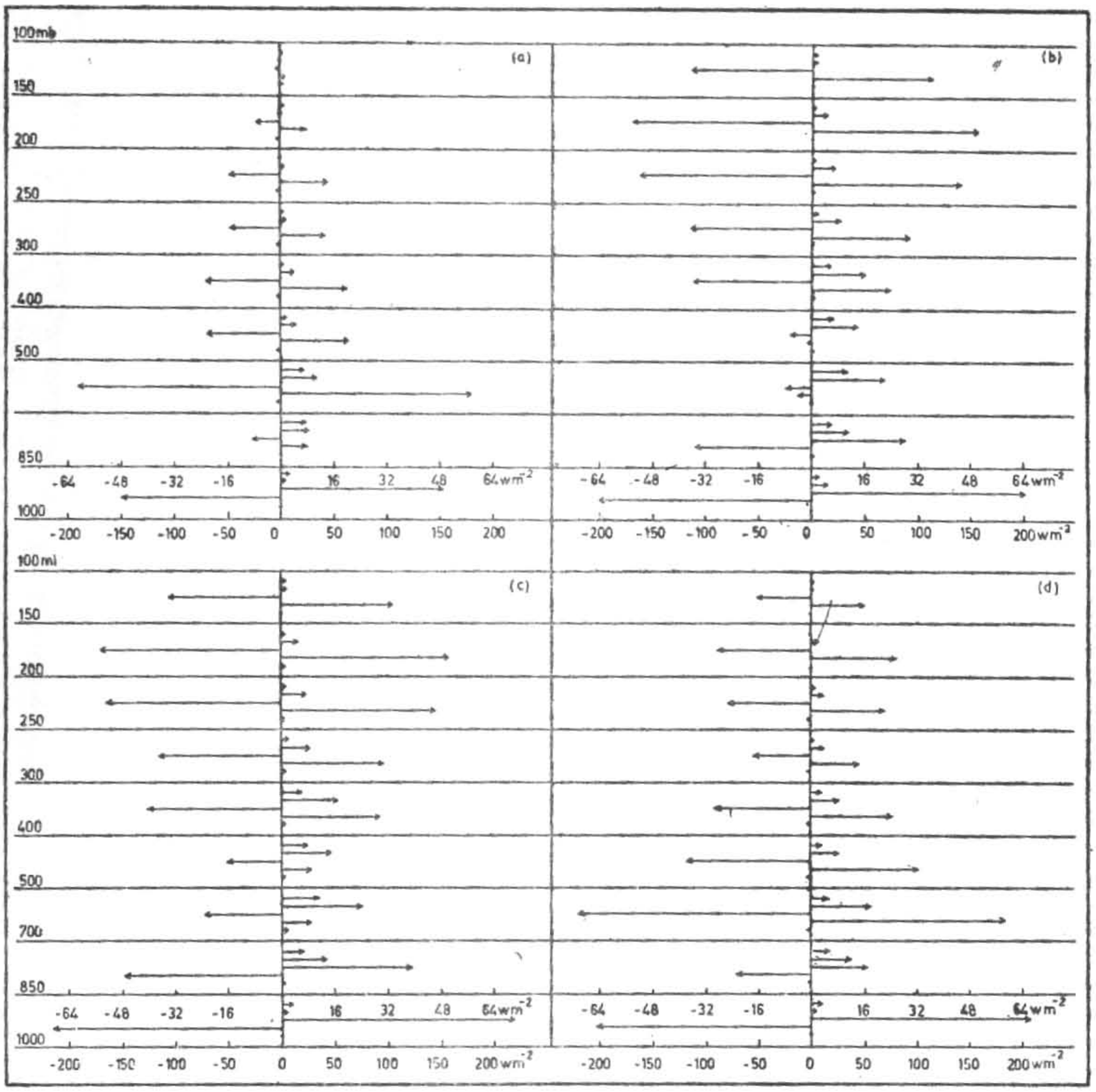

Fig. 7. Time averaged vertical distribution of various terms in the heat budget for the period :

(a) 16-31 May 1979, (b) 1-15 June 1979

(c) 16-30 June 1979 (d) 1-15 July 1979

In each pressure layer the various terms; storage, horizontal flux divergence, vertical flux divergence, adiabatic conversion and diabatic heating are represented by the arrows from the bottom to the top respectively.

increases by almost 2 times during 3 June to 6 July. The net positive adiabatic conversion indicate rising motion on the average and the physical mechanism causing the rapid increase of this parameter may be explained as increase of available energy for conversion to atmospheric motion during active monsoon period. The daily variation of this parameter is almost same as that of horizontal mass flux.

4.3. *Time averaged vertical distribution of various terms of budget equation*

In the tropical region under consideration there is remarkable change in the flow patterns of lower and upper troposphere during monsoon season (Figs. 1-4). Therefore it may be interesting to study the vertical profile of various terms of the budget equation. For this purpose the entire atmospheric column (1000-100 mb) has been divided into 9 layers based on the ten standard atmospheric levels for which the observations are made, *viz.,* 1000, 850, 700, 500, 400, 300, 250, 200, 150 and 100 mb, and the computations are made for each of these nine layers. The results are presented in Fig. 7.

Following are some of the features of the time averaged vertical profiles of the heat budget parameters in four different phases :

(1) The local change of heat energy (heat storage) is very small over the entire atmosphere in all the phases and does not depict any significant feature.

(2) In general, the horizontal and vertical heat flux divergences are very large and to a large extent counter balance each other.

There is a strong low level horizontal convergence of heat up to 850 mb in Phase I which further extends vertically up to 500 mb in Phase II and up to 700 mb in the remaining phases. However, the horizontal convergence of heat in 1000-850 mb and 850-700 mb layers increases from Phase II to Phase III but decreases considerably during Phase IV.

Though the horizontal import of total potential energy into the region is almost same in 1000-850 mb layer during Phases II and IV, it is 53 per cent higher in Phase II in comparison to Phase IV in 850-700 mb layer. This may be due to the weakening of vertical extent of monsoon activity in the later part of Phase IV.

During Phase I there is horizontal divergence of heat energy from 850-100 mb while in Phase II horizontal transport from the region is confined only between 500 & 100 mb layer. In Phases III and IV horizontal divergence extends from 700 to 100 mb. But this heat export in middle troposphere (700-400 mb) during Phase III is much weaker than in Phase IV where its value increases by 4 to 7 times. Further, this export during Phase IV in middle troposphere is comparable to that in Phase I. This indicates that the prevailing conditions in the middle troposphere during Phase IV become similar to Phase I.

In the upper troposphere (400-100 mb) horizontal divergence of heat energy is observed in all the phases. It is interesting to note that while the magnitude of horizontal export decreases vertically from layer to layer during Phase I, in the remaining phases its value increases vertically and attain maximum value in the 200-150 mb layer, thereafter, it decreases with height. This nature of horizontal transport in the later three phases may be only due to the presence of Tropical Easterly Jet with core of maximum wind between 200 & 150 mb. Strong horizontal divergence in this jet level is maintained at the same value during Phases II and III while it decreases by 50 per cent in Phase IV. This decrease may be attributed to the weakening of monsoon activity in the later part of Phase IV.

(3) The positive value of vertical flux indicates the rising motion while the negative value show sinking motion in the layers. Upward fluxes are associated with the horizontal convergence of heat and downward hea fluxes are followed by the horizontal export and thus compensates each other in the net three dimensional heat transport in a particular atmospheric layer.

The nature of vertical variation of net vertical heat flux and its magnitude is almost similar to that of horizontal flux for each layer during all the four phases. Thus, in general there is strong upward heat flux in the lower troposphere and downward heat flux in the upper troposphere with its maximum at the jet level.

(4) The adiabatic conversion of available potential energy to kinetic energy ($-\omega\alpha$) remains positive in the entire troposphere during all the four phases. This indicates the release of available potential energy at large scales as a source of kinetic energy and rising motion on the average. The magnitude of $-\omega\alpha$ is higher in all the layers during Phases II and III compared to corresponding layers in Phases I and IV. This may be due to the fact that during Phases II and III monsoon was more active than in Phases I and IV. The vertical profile of $-\omega\alpha$ shows maximum in the middle troposphere in Phases I and IV while the maxima is seen in the upper troposphere (400-200 mb) during active monsoon period. This level of maxima in upper troposphere agrees with the findings of Nitta (1970), Wallsee (1972) and Kung (1974) for eddy conversion over the tropics. For a limited

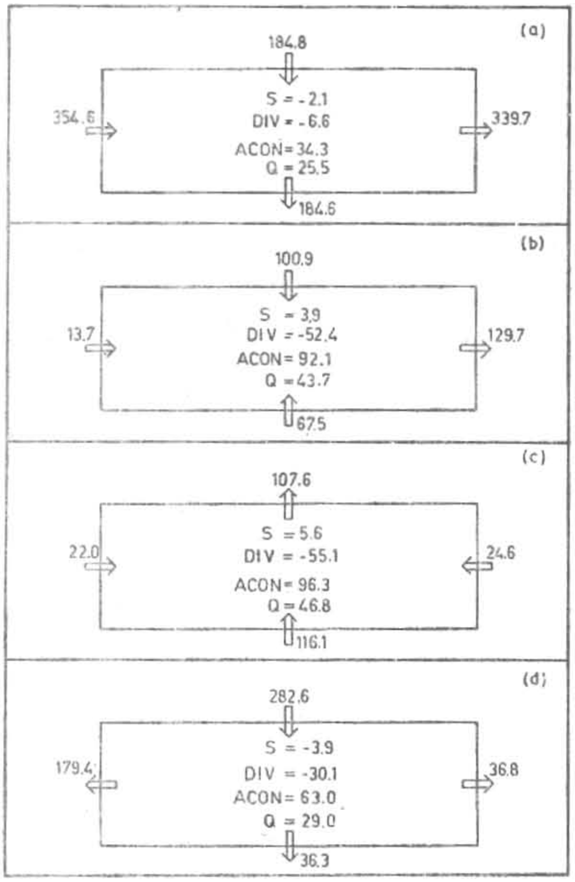

Fig. 8. Schematic diagrams of the mean heat budget for the period : (a) 16-31 May, (b) 1-15 June, (c) 16-30 June and (d) 1-15 July 1979 (Units are in Wm^{-2})

region, in terms of the mean energy budget, the majority of the released available potential energy is exported by the horizontal mass flux and only a fraction is utilised to generate kinetic energy (Fig. 6). However, these two levels are the major source of kinetic energy to maintain low level westerlies and upper level easterlies during monsoon season.

(5) The net diabatic heating is almost positive throughout the entire atmosphere during all the phases, which indicates the warming of the tropical atmosphere during summer (Newell *et al.* 1974).

During Phases I and IV the diabatic heating exhibits single maxima close to the ground (1000-850 mb) and decreases vertically. This maximum diabatic heating at the ground may be attributed to the strong heat transfer from the relatively warm ocean and land surfaces by turbulent mechanism. In Phases II and III two maxima are observed, one at the ground level (1000-850 mb) and the other in the middle troposphere (500-400 mb). The cause of the occurrence of first maximum may be the same as that in Phases I and IV, the second maximum may be explained due to strong latent heating in the middle troposphere through condensation of water vapour. From this it may be inferred that the disappearance of second maxima in the Phase IV is due to the weakening of monsoon activity in later part of that phase.

4.4. *Space time average of various parameters of heat budget equation*

The results are averaged horizontally over large area, vertically up to 100 mb and over a time period of fifteen days, which helps to smooth out random errors. The results are presented in Fig. 8.

Following are some of the features of net sensible heat budget parameters over the region considered:

(*a*) During Phases II and III the net sensible heat storage, adiabatic conversion of available potential energy to KE and diabatic heating terms increase considerably from Phase I. Further, these terms show a decreasing trend in

Phase IV, which may be considered as the indicator of the decrease in the intensity of monsoon activity in the later part of this phase.

(*b*) Throughout the entire period there is net horizontal convergence of sensible heat into the region. This horizontal import of sensible heat increases remarkably during active monsoon period while a decreasing trend in convergence is seen before the break monsoon condition which prevailed over India at the end of Phase IV.

The fluxes through the lateral boundaries play an important role in net import of sensible heat into the region, in particular, from southern hemisphere. It may be seen from the figure that there is influx of sensible heat through southern boundary of the region during Phases II and III while there is net outflux through this boundary in the remaining phases.

5. Conclusions

On the basis of the above results, following general conclusions may be drawn :

(*i*) The various parameters of heat budget depict the real picture of the different important phases, *e.g.*, onset, active (maintenance) and break monsoon periods.

(*ii*) Daily variation of enthalpy, horizontal convergence of heat, net adiabatic conversion and diabatic heating show an increasing trend from 3 to 6 June and thereafter maintained at a higher value until 6 July. The increase in the value of these parameters, which are the characteristic indicators of atmospheric activities, starts about 2 weeks before the onset of monsoon over Kerala coast and persists at high values throughout the active monsoon period.

(*iii*) The heat budget parameters show a decreasing trend after 6 July. About a week before the break monsoon prevailed over Indian subcontinent (started on 16 July) the value of these parameters become comparable to that during pre-onset period, thus indicating the weakening of monsoon activity.

(*iv*) The large scale heat budget parameters are good and reliable indicator of monsoon activity over Indian subcontinent, which confirms the findings of theoretical studies that summer monsoon activity is not a synoptic scale process like monsoon depression or tropical cyclones but is significantly influenced by large scale flows (Gilchrist 1977, Washington 1980). Further this study indicates important role of southern hemispheric tropical flow.

(*v*) From the above results it may be inferred that this studies has potential for a medium range forecast of the monsoon activity, such as, the date of onset and break monsoon over India from the day to day nature of heat budget parameters.

The above conclusions are drawn on the basis of the study carried out by using only one year data set (FGGE), which limits the confirmation of the above findings. However, this is the best and single data set available at present in its complete form for a data sparse tropical oceanic region and thus encourages the above findings.

As India is venturing into the geostationary satellite era in the near future, it may be possible to have adequate information about the large scale flow over the monsoon region which is covered by two third oceanic area. It is proposed to confirm the findings of this study with such complete data sets, as outcome of INSAT project, which may possibly help operational meteorologists to make accurate prediction of monsoon activities well in advance.

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