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

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सार – ग्रीष्म मानसून के शुभारंभ और उसकी प्रक्रिया पर बड़े पैमाने पर व्याप्त नमी और नमस्थितिक ऊर्जा बजट के प्रभाव का अन्वेषण किया गया है । इस अध्ययन के लिए आंकड़ों का आधार मई-जून 1979 के दौरान 20° द० से 40° उ० तक तथा 0°पू० से 150° पू० तक की उष्णकटिबन्धीय पट्टी पर दिन में दो बार लिए गए तापमान आपेक्षित आर्द्रता भूविभव एवं पवन क्षेत्रों का प्रथम जी० ए० आर० पी० भूमंडलीय प्रयोग (एफ० जी० जी० आई०) स्तर III बी का विश्लेषण है ।

मानसून की प्रक्रियाओं पर पड़ने वाले प्रभाव को ज्ञात करने के लिए गुप्त उष्मा ऊर्जा (ग०उ०ऊ०) एवं नमस्थितिक ऊर्जा (न०स्थि० ऊ०) बजट समीकरण के विभिन्न पदों का दैनिक विचरण उर्ध्वाधर बंटन और आवधिक औसत की काफी बारीकी से जांच की गई है । इस अध्ययन से केरल तट पर मानसून के शुरु होने से लगभग 2 सप्ताह पूर्व कुल गु० उ० ऊ.० नमी के क्षेतिज अभिसरण और डायबेटिक नमी अभिगम (वाष्पन की अपेक्षा शीतलन की अधिकता का संकेतक) में महत्वपूर्ण वृद्धि के होने का संकेत मिलता है । इसके बाद मानसून भंजन की स्थिति, जो भारत में 16 जुलाई 1979 को प्रारम्भ हुई, के लगभग एक सप्ताह पहले नमी क्षेतिज अभिसरण और नमी अभिगम में ह्रास की प्रवृति देखी गई है । फिर भी, मानसून के अग्रगमन के साथ नमस्थितिक ऊर्जा बजट समीकरण के विभिन्न पद कोई महत्वपूर्ण प्रवृति को चित्रित नहीं करते । ऊर्ध्वाधर बंटन, आवधिक औसत और परिसीमा अभिवाह भी उपरोक्त तथ्यों की पुष्टि करते हैं ।

ABSTRACT. The effect of large scale moisture and moist static energy (MSE) budget on the onset and activities of summer monsoon is investigated. The data base for this study consists of twice daily First GARP Global Experiment (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, during May-July 1979.

The daily variation, vertical distribution and period averages of the various terms in latent heat energy (LHE) and MSE budget equation are closely examined to find out their influence on the activities of monsoon. The study indicates significant increase in the net LHE, horizontal convergence of moisture and diabatic moisture sink (indicator of excess condensation than evaporation) about two week before the onset of monsoon over Kerala coast. Further, a decreasing trend is observed in horizontal convergence of moisture and moisture sink about one week before the break monsoon condition, which started over India on 16 July 1979. However, the various terms of the MSE budget equation do not depict any significant trend with the advance of the monsoon. The vertical distribution, period averages and the boundary fluxes also confirm the above findings.

1. Introduction

The present paper is the continuation of the earlier work done by the authors (Mohanty *et al.* 1982) in order to have the complete picture of the characteristic thermodynamic structure of the monsoon circulation. The summer monsoonal flow is one of the most persistent features of the earth's atmosphere. The association of heat and moisture budgets with the monsoon circulation is well recognised by various investigators (Riehl 1980; Pisharoty 1965; Saha and Bavadekar 1973; Bunker 1965 etc).

Due to the inhomogeneous moisture distribution in the atmosphere, its analysis is very difficult job, especially, in a data sparse tropical belt monsoon region. Due to the non-availability of reliable moisture data over the monsoon region, there appears to be very few number of work in the literature related to Asian summer monsoon, confined to a limited region (Pisharoty

1965; Anjaneyulu 1969; Saha and Bavadekar 1973 etc).

In the present paper an attempt has been made to study the moisture and moist static energy budget over a large monsoon area with the help of a reliable and complete data set, obtained first time over this area. The effect of latent heat energy and moist static energy on the 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 aspects of the summer monsoon.

2. The budget equation

The latent heat energy and moist static energy budget equations in the flux form in pressure co-ordinates may be written as :

$$\frac{\partial Lq}{\partial t} + \nabla\cdot(Lq\mathbf{V}) + \frac{\partial(Lq\omega)}{\partial p} = L(E-C) + LH \tag{1}$$

$$\frac{\partial h}{\partial t} + \nabla\cdot(h\mathbf{V}) + \frac{\partial(h\omega)}{\partial p} = Q_R + LH + SH \tag{2}$$

where,

$h = c_p T + gz + Lq$,

L=latent heat of evaporation,

q=specific humidity,

Q_R=diabatic heating due to radiative effects,

E=evaporation, C=condensation,

LH and SH=latent and sensible heat flux at the earth's surface due to turbulent transfer respectively, and other terms have their usual meaning.

These equations are integrated over a closed volume (Mohanty *et al.* 1982) leading to the following space averaged budget equations :

$$\frac{\partial \overline{Lq}}{\partial t} + \nabla\cdot(\overline{Lq\mathbf{V}}) = \overline{L(E-C)} + \hat{LH} \tag{3}$$

i.e., $S + DIV = MS$

and

$$\frac{\partial \overline{h}}{\partial t} + \nabla\cdot(\overline{h\mathbf{V}}) = \overline{Q_R} + \hat{LH} + \hat{SH} \tag{4}$$

i.e., $S + DIV = RLS$

where, the symbol $\wedge$ stands for horizontal average at the earth's surface and

S=rate of change of latent heat energy/moist static energy,

DIV=rate of outflux of latent heat energy/moist static energy,

MS=diabatic source/sink of latent heat energy

RLS=net diabatic fluxes of radiation, latent heat and sensible heat needed for the balance of the moist static energy budget equation.

3. Data set and analysis procedure

The data base used for this study is the same as that of the earlier work of the authors (Mohanty *et al.* 1982) for the tropical belt 20 deg. S to 40 deg. N and 0 deg. E to 150 deg. E. As in the earlier work the two months periods (16 May - 15 July) has been divided into four phases, each of fifteen days duration.

The ω - field, required for this budget study, is obtained from horizontal wind fields by kinematic method as discussed in the Part I of the study.

The numerical scheme and analysis procedure followed in this study has been detailed in the earlier work of the authors (Mohanty *et al.* 1982).

4. Interpretation of results

Daily variation, vertical distribution and period averages of various terms in the latent heat energy and moist static energy budget equations are closely examined to find out their influence on the activities of Indian summer monsoon.

4.1. *Daily veriation of various parameters of the latent heat energy budget equation*

Following are some of the features of daily variation of the vertically integrated latent heat energy and parameters of the moisture budget equation (Fig. 1) :

1. The daily variation of the net latent heat energy decreases form 16 - 24 May and then increases steadily upto 5 June (from 95×10^6-105×10^6Jm^{-2}). Thereafter, it is almost maintained till the end of phase IV in the range 102×10^6-105×10^6 Jm^{-2}. This indicates that with the advance of the monsoon the average moisture content of the atmosphere increases by about 10 per cent and remains almost unchanged during monsoon. The main source of moisture in the atmosphere comes from the evaporation over the ocean surface through turbulent moisture transport. Since during monsoon season the moisture distribution close to air-sea interface is almost invariable and as low level wind speed also does not change remarkably after the onset of the monsoon, therefore, the total moisture content may not be affected very much.

2. There is no distinct trend in the total moisture storage of the atmosphere during entire period.

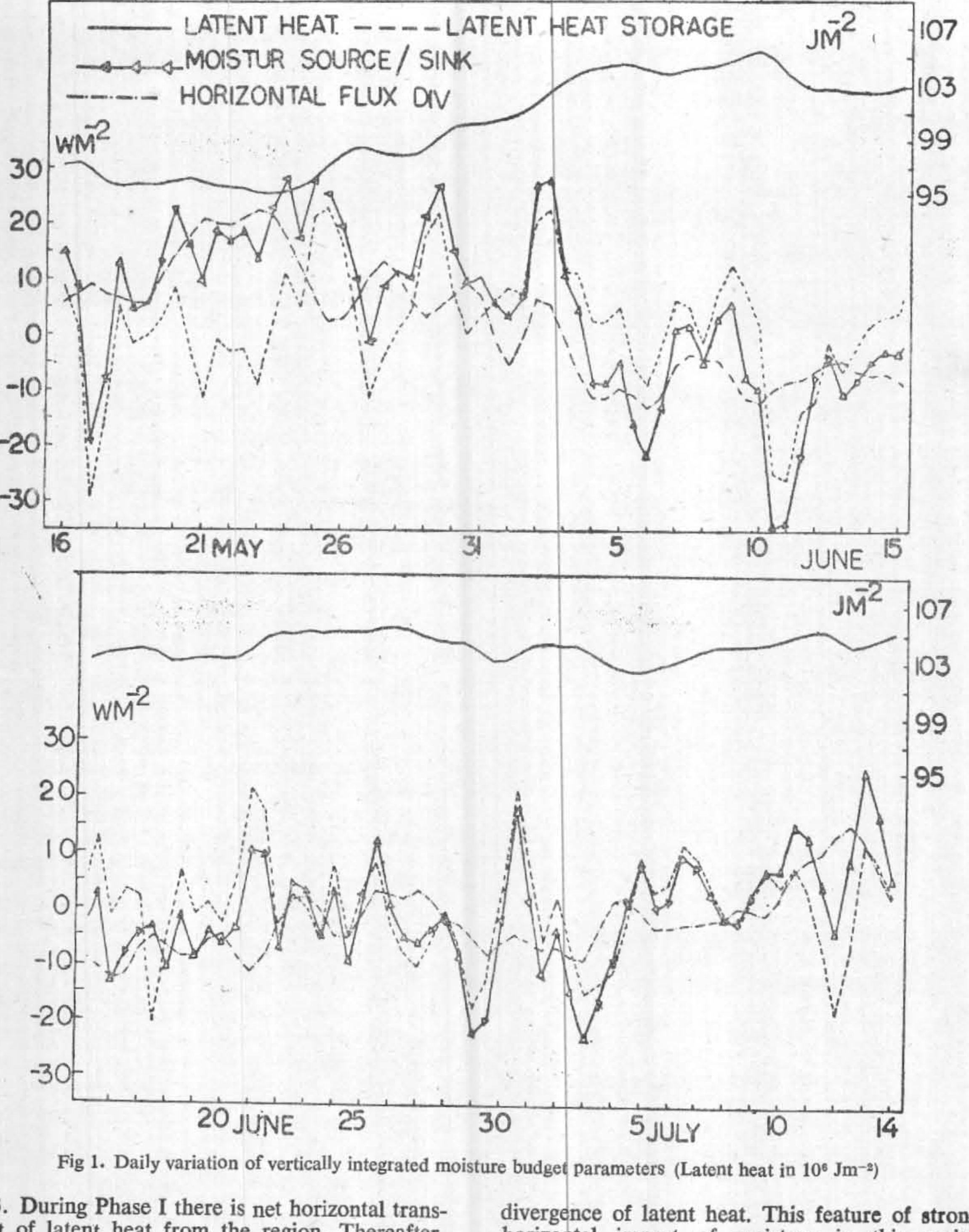

Fig 1. Daily variation of vertically integrated moisture budget parameters (Latent heat in 10^6 Jm^{-2})

3. During Phase I there is net horizontal transport of latent heat from the region. Thereafter, starting from 3 June to 3 July net horizontal influx of latent heat to the region with the exception of two isolated events (not exceeding more than two days) are observed. This convergence may be attributed to the strong transport of moisture from Southern Indian Ocean and Western Pacific during this period. In the remaining period of Phase IV there is almost horizontal divergence of latent heat. This feature of strong horizontal import of moisture in this region during the monsoon period (3 June - 3 July) agrees well with the heat convergence during the same period (Mohanty *et al.* 1982).

4. The diabatic contribution (source or sink) of net moisture in the observed atmosphere is estimated by residual method. Diabatic moisture

source stands for excessive evaporation compared to condensation over the entire atmosphere while diabatic moisture sink signifies the excessive condensation over evaporation.

During Phase I there is diabatic source of moisture with the exception 17-18 May, which indicates excess of evaporation over that of condensation before the onset of monsoon. In general, during 4 June to 4 July the net condensation exceeds the evaporation, however, there are a few occasions when evaporation exceeds condensation but none of these exceptions continue for more than a day. Remaining period of the Phase IV is marked with excess evaporation, which may be due to the decrease in condensation just before the break monsoon condition over Indian subcontinent.

Characteristically persistent excess condensation during 4 June - 4 July may be attributed to the active monsoon period, which is also indicated by other parameters. In particular, during this period increase in diabatic heating and enthalpy (Mohanty *et al.* 1982) confirm the excess release of latent heat due to condensation of water vapour. Strong horizontal convergence of heat and moisture along with increased rising motion (Mohanty *et al.* 1982) further supports above conclusions. It is interesting to note that each outburst of excess condensation is associated with rapid decrease of moisture storage and *vice-versa*. Further, during active monsoon period (4 June - 4 July) every excess storage of moisture leads to an outburst of condensation/precipitation. The physical mechanism behind this diabatic process may be expected in a highly moist (nearly saturated) lower and middle troposphere where any extra addition of moisture (increase of storage) may lead to precipitation.

4.2. *Daily variation of various parameters of most static energy budget equation*

Following are some of the features of daily variation of the vertically integrated moist static energy and its budget parameters (Fig. 2):

(1) The daily variation of the net moist static energy (MSC) is almost steady during the Phase I. Thereafter, it gradually increases from 31 May - 10 June (increases by about 0.4 per cent in 10 days). The MSE is almost maintained at this high value till 20 June. From 20 - 26 June an increase of about 0.2 per cent is observed and in the remaining period it remains almost steady. The maximum percentage difference between lowest and highest value of MSE does not exceed 1 per cent, indicating the invariability of the net moist static energy of the atmosphere during monsoon period.

(2) There is no distinct trend in the daily variation of total moist static energy storage of the atmosphere during the entire period.

(3) The MSE budget shows the net horizontal export of moist static energy from the region. This horizontal divergence lies in the range of 25 - 50 Wm^{-2} and does not show any definite trend. In order to maintain the net convergence of heat (Mohanty *et al.* 1982) and moisture (Fig. 1) mainly through the lower troposphere there must be a strong net divergence from the region mainly through the upper troposphere. It may be seen that the net mass divergence increases considerably during active monsoon period (Mohanty *et al.* 1982) and therefore leads to the positive horizontal flux divergence of MSE.

(4) The diabatic contributions to the net moist static energy are mainly radiation and subgrid scale processes such as turbulent flux of latent and sensible heat at the earth's surface, which are estimated by the residual method. The net diabatic contribution of moist static energy is always positive throughout the period and does not show any definite trend and lies between 10 - 75 Wm^{-2}. Studies of various workers (Newell *et al.* 1974) shows consistent net heating in the tropics during summer which is in agreement with our finding of positive diabatic contribution.

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

Following are some of the features of the time averaged vertical profiles of the latent heat energy budget parameters in different phases (Fig. 3):

(1) The local change of moisture (storage) is very small during all the phases. However, its value is significantly higher in the lower troposphere during Phase I. During Phase II the storage is positive and almost same throughout the vertical column of the atmosphere. In Phase III the storage is almost negligible which picks up again in Phase IV. This may be explained

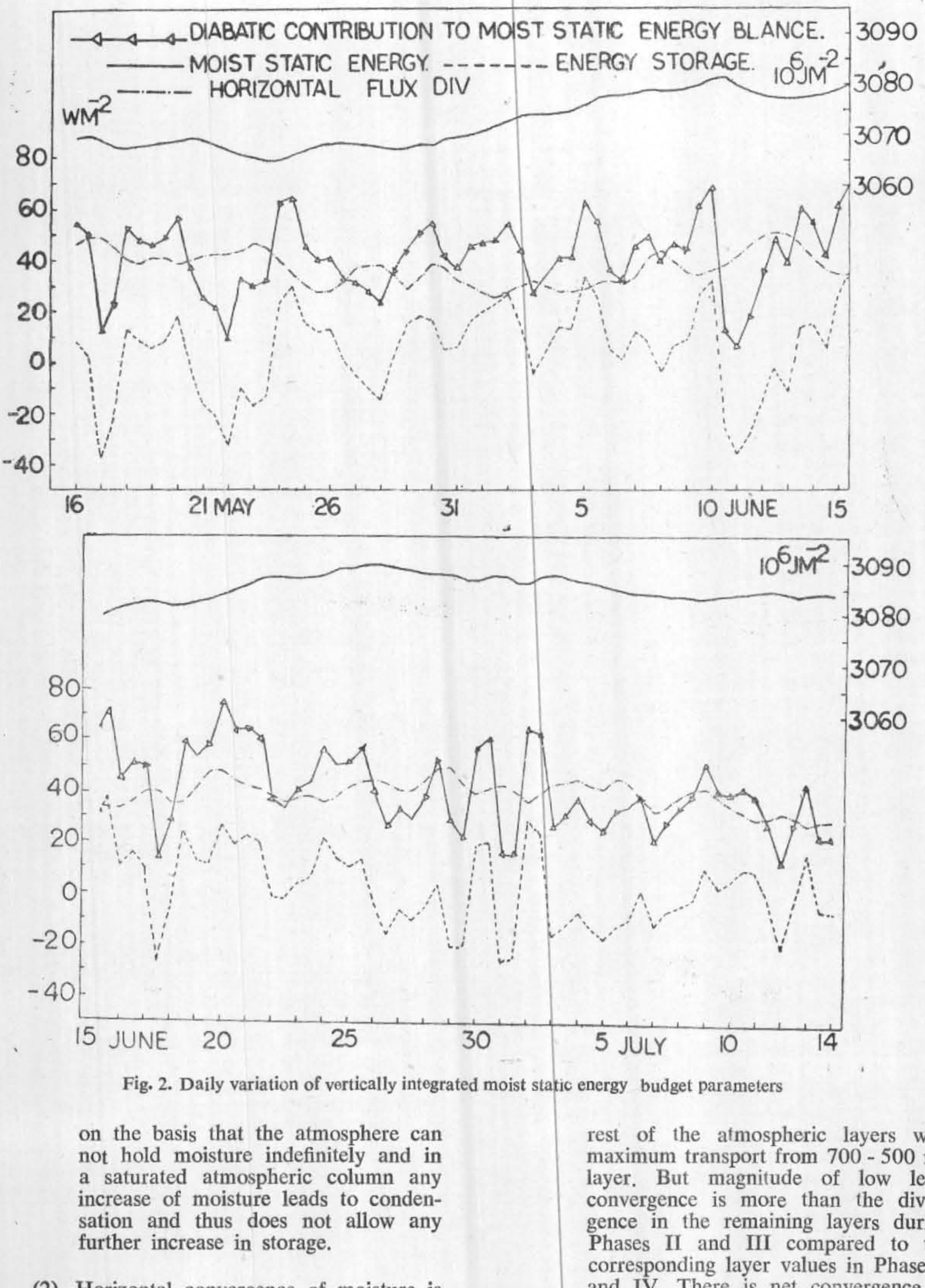

Fig. 2. Daily variation of vertically integrated moist static energy budget parameters

on the basis that the atmosphere can not hold moisture indefinitely and in a saturated atmospheric column any increase of moisture leads to condensation and thus does not allow any further increase in storage.

(2) Horizontal convergence of moisture is confined only to the surface layer during all the phases. There is transport of moisture from the region in rest of the atmospheric layers with maximum transport from 700 - 500 mb layer. But magnitude of low level convergence is more than the divergence in the remaining layers during Phases II and III compared to the corresponding layer values in Phases I and IV. There is net convergence in Phases II & III and net divergence in remaining phases. The divergence in Phase I is almost ten times higher than

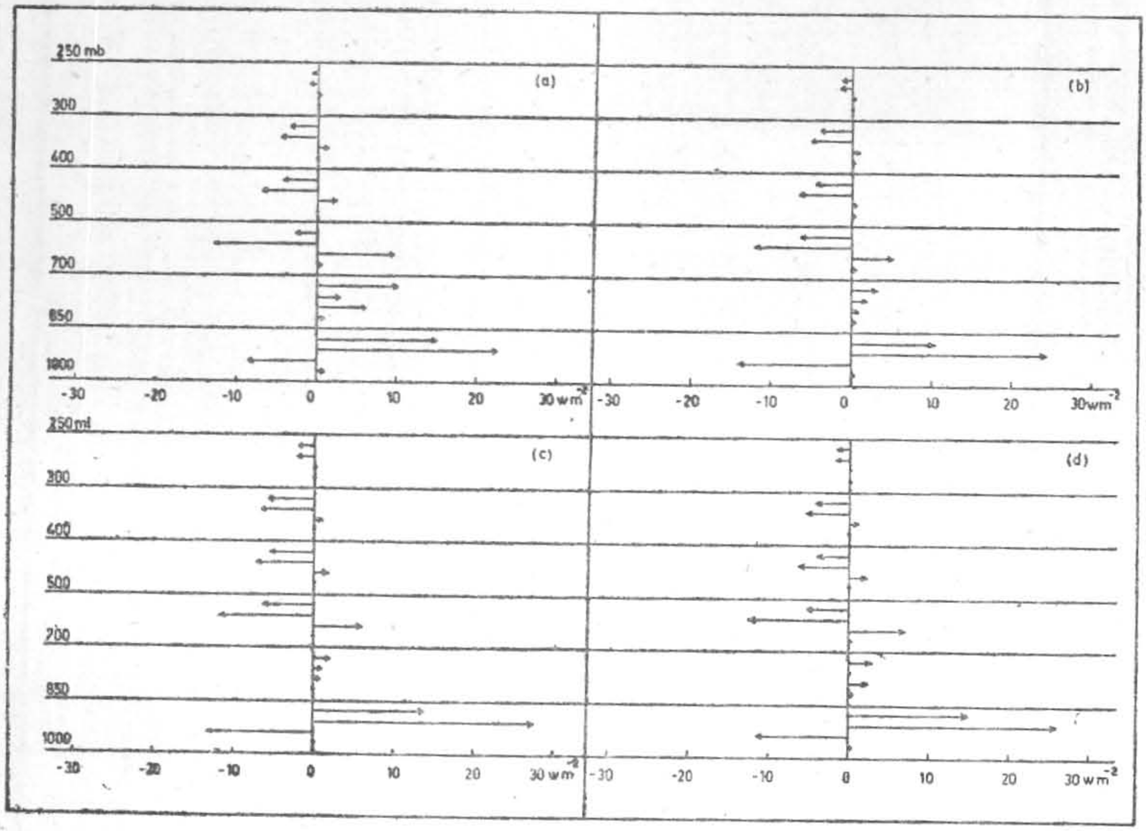

Fig. 3. Time averaged vertical distribution of various terms in moisture budget for the period (a) 16-31 May, (b) 1-15 June, (c) 16-30 June and (d) 1-15 July 1979. In each pressure layer the various terms : storage horizontal flux, vertical flux and moisture source/sink are represented by the arrows from the bottom to the top respectively

that in Phase IV. These results indicate that the horizontal flux divergence plays an important role in monsoon activity by supplying excess moisture to the region which releases diabatic heating in the atmosphere through the process of condensation.

(3) Unlike the case of heat flux (Mohanty *et al.* 1982), the vertical flux of moisture is higher than the horizontal flux. However, this difference is maximum (more than 100 per cent) in the surface layer with minimum difference observed in 850 - 700 mb and 300 - 250 mb during all the four phases. In general, the vertical profile of vertical moisture flux during entire period exhibit the same characteristics. In the lower troposphere (1000-700 mb) there is upward transport of moisture while in the remaining layer (700-250 mb) there is sinking of moisture. Maximum upward transport is observed in the surface layer and maximum downward flux is seen in the 500 - 400 mb layer.

(4) The residue indicates that the lower troposphere (1000 - 700 mb) is the moisture source and remaining layers act as moisture sink during the entire period. The net vertical distribution indicates that the condensation exceeds evaporation during active monsoon period while evaporation exceeds condensation in the Phases I and II. This may be attributed to the high amount of precipitation during active monsoon compared to other periods. The vertical distribution shows that the source of maximum moisture is the surface layer, while maximum sink is in the 500 - 400 mb layer during all the fiur phases. The strong condensation in the middle troposphere and large evaporation in the surface layer is mainly needed to balance the strong vertical transport of humidity. The maximum condensation in the 500 - 400 mb layer coincides with the maximum diabatic heating in the middle troposphere (Mohanty *et al.* 1982), thus confirms the maximum release of latent heat due to condensation of water vapour in that layer.

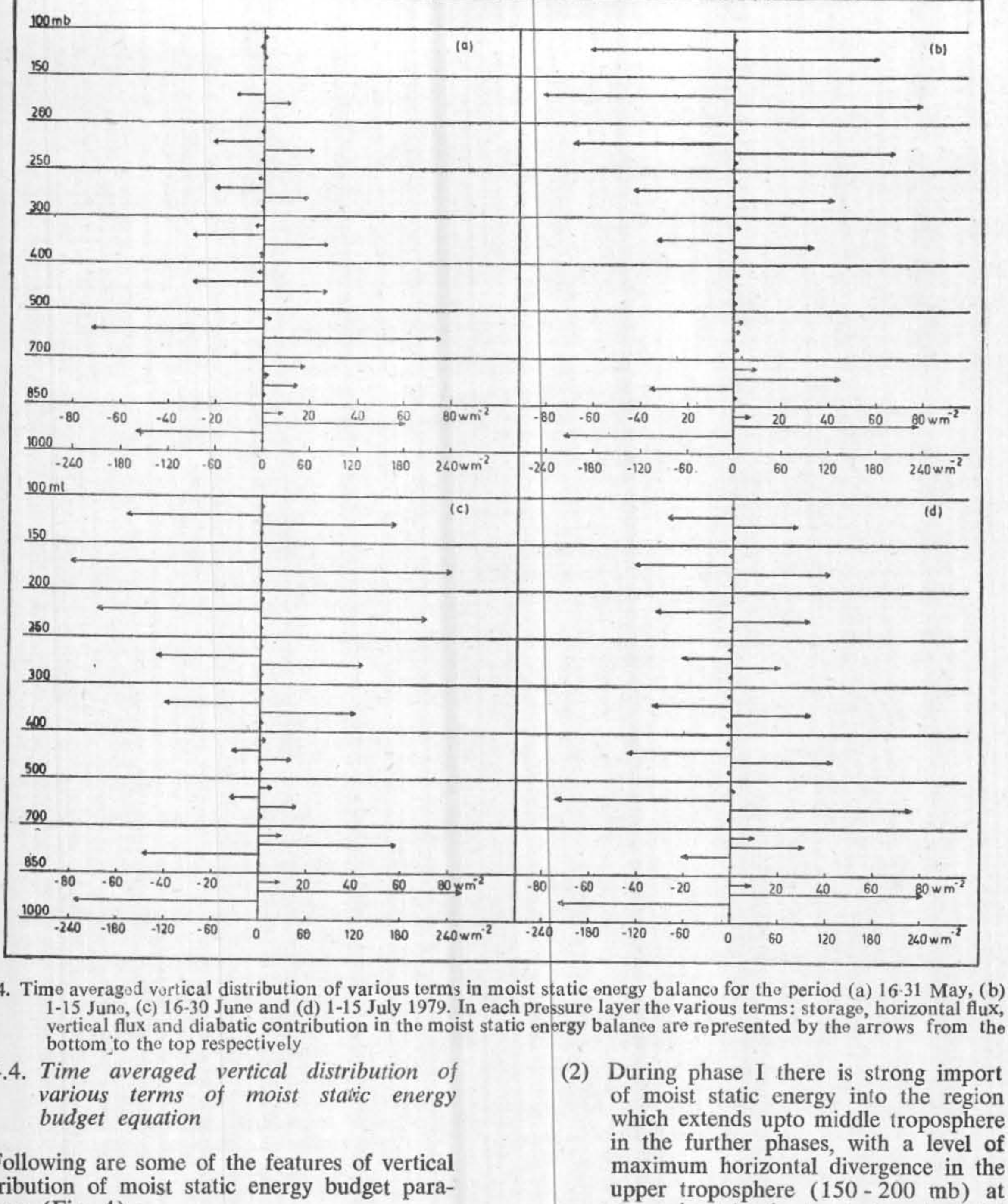

Fig 4. Time averaged vertical distribution of various terms in moist static energy balance for the period (a) 16-31 May, (b) 1-15 June, (c) 16-30 June and (d) 1-15 July 1979. In each pressure layer the various terms: storage, horizontal flux, vertical flux and diabatic contribution in the moist static energy balance are represented by the arrows from the bottom to the top respectively

4.4. *Time averaged vertical distribution of various terms of moist static energy budget equation*

Following are some of the features of vertical distribution of moist static energy budget parameters (Fig. 4) :

(1) The storage of moist static energy is very small over the entire atmosphere in all the phases. There is increase (positive) in local change of MSE in the lower troposphere and decrease (negative) in the remaining layers during Phases I and IV while there is increase in local change at all the levels during active monsoon with maxima in mid-troposphere. Thus, the net MSE storage is more in phases II and III than in I and IV.

(2) During phase I there is strong import of moist static energy into the region which extends upto middle troposphere in the further phases, with a level of maximum horizontal divergence in the upper troposphere (150 - 200 mb) at approximately the tropical easterly jet stream level. The net horizontal flux divergence of MSE is almost same in all the phases.

(3) In general horizontal and vertical fluxes are very large and to a large extent compensate each other. The difference between these fluxes is maximum close to the surface which decreases considerably with height. In the lower troposphere (1000 - 700 mb) there is upward transport in all the phases with maximum value in the surface layer.

In the remaining layers there is, in general, downward transport of MSE, with maximum in the upper troposphere at approximately the easterly jet stream level. The nature of the vertical variation of this flux is similar to that of sensible heat (Mohanty *et al.* 1982).

(4) The residue which contributes towards the moist static energy balance in the atmosphere is positive in the lower troposphere (1000 - 500 mb) during all the four phases. This may be due to upward transport of latent heat and sensible heat from relatively warm ocean and land surfaces through turbulent transfer processes. During phases I and IV there is a sink of the diabatic contribution to the MSE in the 500 - 200 mb layer which may be attributed to the radiative cooling in the upper atmosphere. During active monsoon the upper troposphere serves as a diabatic source to MSE, though the magnitude of this is very less compared to the lower troposphere. This contrast in the upper troposphere during Phases II and III may be due to the absorption of radiation by excess water content and reflection of solar radiation from the top of cloud cover, which is more during active monsoon period.

4.5. *Space time average of various parameters of latent heat energy budget equation*

Following are some of the features of net moisture budget parameters over the region (Fig. 5) :

(1) The net local change of moisture in the region decreases during the Phases II and III in comparison to Phase I and again an increasing trend is seen during Phase IV. This may be attributed to the fact that during active monsoon period the atmosphere remains almost saturated and does not exhibit any fluctuation. The residue values show that the net condensation exceeds the evaporation during active monsoon while the net evaporation dominates the region during Phases I and IV. This result is in agreement with the fact that there is excess precipitation during active monsoon period. Further, this result agrees well with the sensible heat budget which indicates the increase in diabatic heating and rising motion on the average during the same period (Mohanty *et al.* 1982).

(2) There is net horizontal convergence of moisture into the region during Phases II and III but there is net outflux of moisture during Phases I and IV. There is net influx of moisture through the southern boundary and net outflux through western boundary during entire period. The import of moisture through southern boundary increases considerably after the onset of monsoon and does not show any decreasing trend just before the break of monsoon. There is influx of moisture through the eastern boundary during active monsoon and there is outflux of moisture during Phases I and IV.

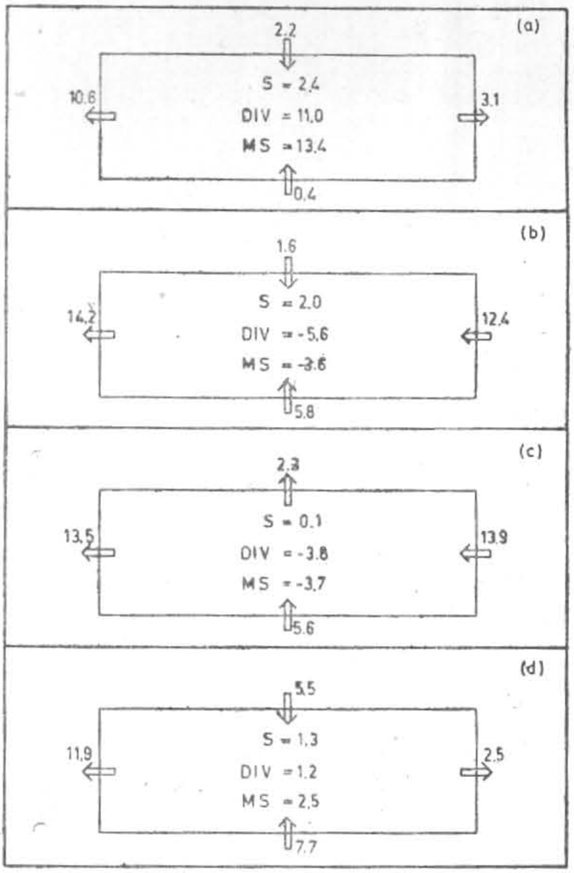

Fig. 5. Schematic diagrams of the mean latent heat balance for the period (a) 16-31 May, (b) 1-15 June (c) 16-30 June and (d) 1-15 July 1979. Units are in Wm^{-2}

4.6. *Space time average of various parameters of moist static energy budget equation*

Following are some of the features of net moist static energy budget parameters over the region (Fig. 6) :

(1) The net storage and the diabatic contribution to moist static energy is more in Phases II and III than in Phases I and IV. These features are similar to those seen in sensible heat budget (Mohanty *et al.* 1982).

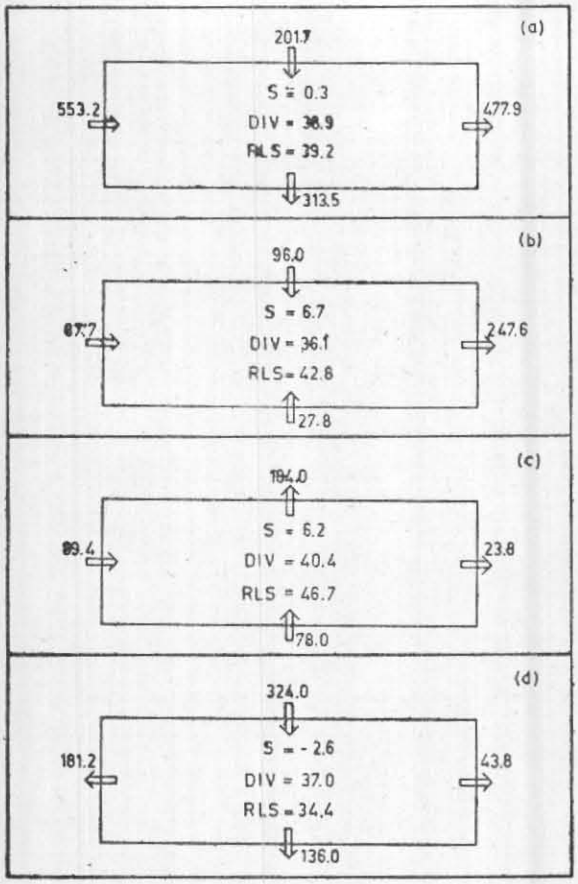

Fig. 6. Schematic diagrams of the mean moist static energy balance for the period (a) 16-31 May, (b) 1-15 June, (c) 16-30 June and (d) 1-15 July 1979. Units are in Wm^{-2}

(2) There is net export of MSE from the region during all the four phases and does not show any remarkable change from phase to phase. During all the four phases there is net outflow of moist static energy across the eastern boundary while the fluxes through other lateral boundaries are similar to that of sensible heat (Mohanty *et al.* 1982).

5. Conclusions

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

(*i*) The various parameters of the moisture budget over a large area depict the real picture of the different important phases, *e.g.*, onset, active and break monsoon periods, similar to that of heat budget parameters (Mohanty *et al.* 1982).

(*ii*) Daily variation of latent heat energy shows an increasing trend from 4 May-5 June and thereafter maintained almost at this level, whereas, horizontal import and diabatic sink of moisture show an increasing trend from 3 - 6 June and thereafter maintained at a higher value until 3 July. The increase in the values of these parameters, which are the characteristic indicators of monsoon activities, starts about 2 week before the onset of monsoon over Kerala coast and persists at high values during active monsoon period.

(*iii*) After 5 July there is net transport of moisture from the region and increase of moisture source, which may be due to decrease in precipitation over a large area under consideration. Thus the daily variation of these parameters indicate a weakening of monsoon about 10 days before the break monsoon prevailed over Indian subcontinent and thus confirms the earlier results on heat budget parameters (Mohanty *et al.* 1982).

(*iv*) Similar to the large scale heat budget parameters, the moisture budget parameters are reliable indicator of monsoon activity over Indian subcontinent. This study also confirms the earlier results that the southern hemispheric tropical circulation plays an important role in the northern hemispheric summer monsoon.

(*v*) From the results of moisture budget and the earlier study on heat budget it may be seen that the daily variation of these budget parameters are consistent and exhibit similar characteristics in different phases of monsoon. It may therefore be inferred that the diagnostic studies have potential for medium range forecast of the monsoon activity, such as, the date of onset and break monsoon over Indian sub-continent from the day to day nature of heat and moisture budget parameters.

(*vi*) The net moist static energy remains almost steady for the entire period as the maximum percentage difference of this value does not exceed 1 per cent. The horizontal flux of MSE is also almost constant (mean = 38.1 Wm^{-2} and standard deviation = 1.7 Wm^{-2} from phase to phase.

(*vii*) The daily variation of the MSE budget parameters do not show any definite trend. It may, therefore, be concluded that the MSE is invariant over a large area of the tropical belt during different phases of monsoon activity.

The above conclusions are drawn on the basis of heat, moisture and moist static energy budgets carried out by one year data set (FGGE). However, all these different budget studies are consistent and are in conformity with each other which encourages the validity of above findings.

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