THE EFFECTS OF DISTURBANCES ON THE TROPICAL CIRCULATION

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1. Introduction

The ascending branch of the Hadly circulation, the intertropical convergence zone (ITCZ), is not a region of a continuous rising, the upwards transport is accomplished by a number of disturbances. This was hypothesized by Riehl and Malkus (1958) and could be established by the satellite observations. The satellite images made it evident that the convection in the tropics (especially over the ocean) is not randomly distributed but organized in certain forms, the so-called cloud clusters.

Their role within the tropical circulation can be summerized by the following processes:

1. They transport mass, water vapor, energy and momentum out of the boundary layer (the source region) upwards into the upper troposphere (the sink region).
2. They generate energy by the release of latent heat within their cloud updrafts.
3. They convert total potential into kinetic energy by the updraft-downdraft circulation.
4. They affect the radiation field by the development of thick cirrus shields.

From these points it becomes clear that the up- and downdrafts of the convective clouds within the cloud clusters are to be known. The cloud mass flux distribution is an important parameter in the investigation of the tropical disturbances. Despite of the important role of the cloud clusters for the tropical circulation not to much is known about these phenomena. Their origin is not yet fully understood. Chang (1970) could show with a time-composite technique applied to satellite images, that the cloud clusters over the Pacific ocean are often associated with the tropical easterly waves. Based on this information Reed and Recker (1971) studied the interaction of the cloud clusters and the waves. Williams and Gray (1973) and Ruprecht and Gray (1976) accomplished composited studies of the cloud clusters over the Pacific ocean and the West Indies. The mean wind, humidity and temperature fields could be described and agreed in general with the findings of Reed and Recker's composite wave.

The internal structure, however, was still unknown. The GATE experiment (summer 1974) aimed to investigate the internal structure of the cloud clusters and their interactions with the larger scales.

In the following some results will be shown of the cloud cluster studies done at the University of Cologne based on GATE data. Two problems will be discussed: the relation of the divergence field and the rainfall and the energy budget. A strong low-level convergence is a necessary condition for the development of a cloud cluster and rainfall can be considered as an end-product. Thus the relation give some evidence about the development of the cloud clusters. The results will show, how the intensification of the rainfall and the convective activity is related to the divergence field. The energy budget results demonstrate the importance of the up- and downdraft circulation of the cloud clusters.

2. Analysis

The period of Aug. 30 to Sept. 8 1974 is analysed. The rawinsonde observation at the A/B ships, the radar rainfall, satellite images and radar observations at the German research vessel "Planet" provide the data base. The analysis was performed for the triangle -ABC- shown in Fig. 1. An objective analysis method was developed (Ruprecht, 1981a) to derive the temperatures, humidities and winds at the 3 corner points and to calculate the mass, water vapor and

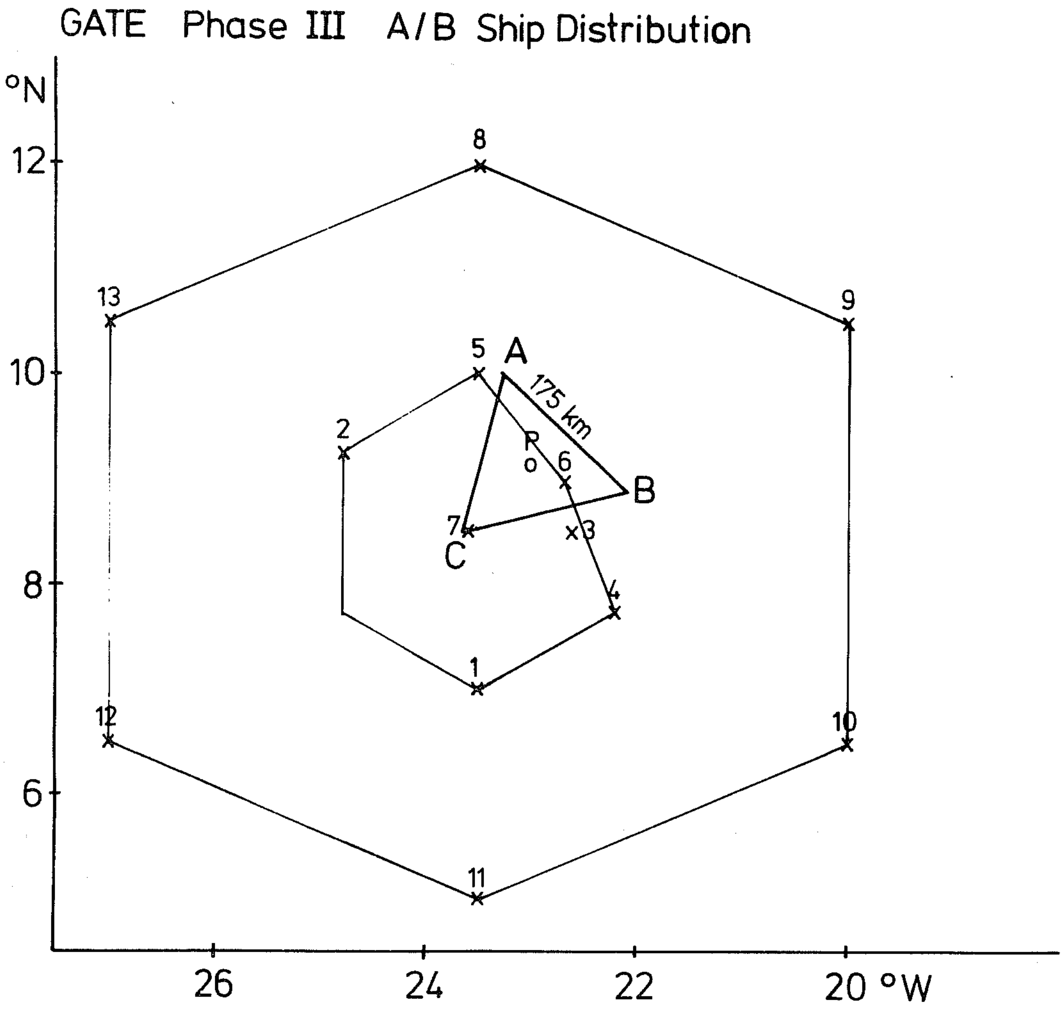

Fig. 1. Position of the triangle -ABC- for which the data analysis is done. P = position of the RV "Planet"

energy divergences. The synoptic situation during the 10 days under investigation is depicted in Fig. 2 by the low-level meridional winds, the radar rainfall, the satellite observations, and the vertical velocities at the 900 mbar level. The meridional winds show a distinct wave form. Rainfall and vertical velocity distributions are well related to the wave structure as described by Thompson et al. (1979). The maximum rainfall is just ahead of the trough and occurs several hours after the maximum of low-level convergence (vertical velocity at 900 mbar).

3. Relation between convergence and rainfall

The investigation of the tropical disturbances leads to two main parameters: the horizontal low-level convergence of mass (and water vapor) and the total precipitation. The first provides the latent heat, hence the energy to drive the system and the second is a product of the system. The relation of both parameters is investigated in numerous studies. For the different tropical regions similar results are found: low-level convergence and rainfall are well correlated, however with a time lag of serval hours (Cho and Ogura, 1974; Johnson, 1978; Nitta, 1978; Brümmer, 1979).

It seems that the time lag depends on the scale of the convergence field (Brümmer, 1979). The compensating sinking is probable one cause for this relation. The sinking occurs not in the immediate but in the larger environment of the cloud ensemlbe and sets in after the deep clouds are developed.

Fig. 3 shows the correlation coefficients between rainfall and vertical velocity at 3 levels with different time lags (positive time lag means the rainfall occurs after the vertical velocity). The low-level convergence (vertical velocity at 900 mbar) occurs 4 to 6 h before the rainfall, but the maximum correlation is found with no

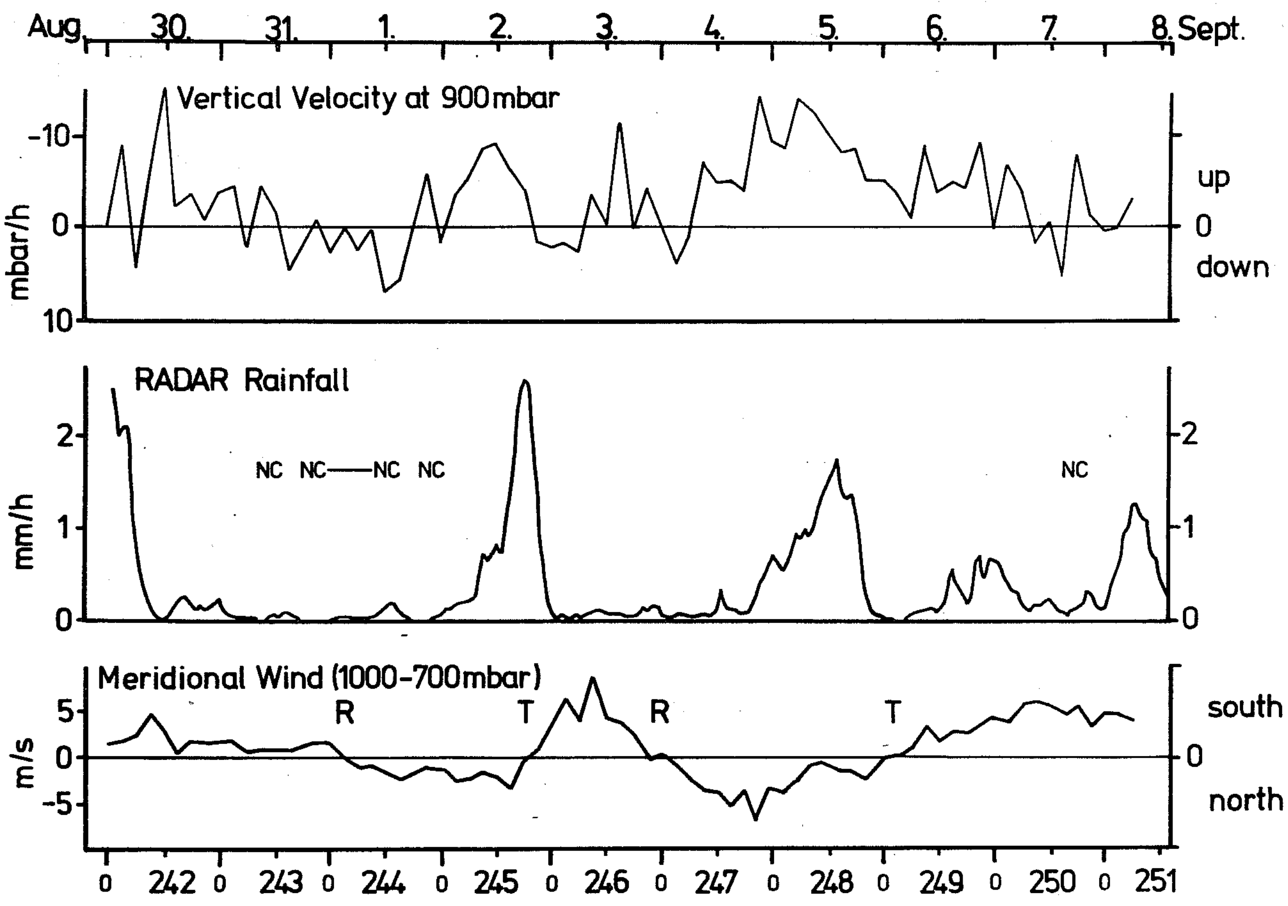

Fig. 2. Time series of the low-level parameters for the period of the analysis (NC = no cloud cluster based on satellite images; T,R = trough, ridge position

time lag for the vertical velocities above 650 mbar. This is clearly seen in the bottom part of Fig. 3 which gives the time lags of the maximum correlation coefficients between rainfall and vertical velocities at all 50 mbar levels between surface and 100 mbar. The thin lines show the range for significant correlation coefficients based on 2 σ (standard deviation).

In order to understand these relations a detailed study was performed. Fig. 4 shows a composite, the mean divergence profiles relative to the rainfall maximum. Weak low-level convergence occurs 12 h prior to the rainfall maximum. The convergence increases during the next 6 h but the depth of the convergent layer ramains shallow. The outflow divergence is found in the middle troposphere around the 500 mbar level. The picture changes totally 3 h before the appearance of rainfall maximum. The low-level convergence decreases but the depth of the convergent layer increases and the outflow divergence is found in the middle and upper troposphere. Finally at the rainfall maximum the two layer model exists which was described as typical for the disturbances over the Pacific ocean and the West Indies by Williams and Gray (1973), Ruprecht and Gray (1976) and Reed and Recker (1971) with a deep inflow layer between surface and 400 mbar and an outflow divergence above. This simple picture could not be verified over the GATE area with the average profiles. Our study shows that low-level convergence during the developing stage of the disturbances paves the way for the development of the deep Cbs. It is responsible for the upwards transport of water vapor into the middle troposphere and for the moistening of this layer thus deep clouds can penetrate the mid troposphere and reach the upper levels. This is confirmed by the vertical profiles of humidity (not shown here, see Ruprecht, 1981a).

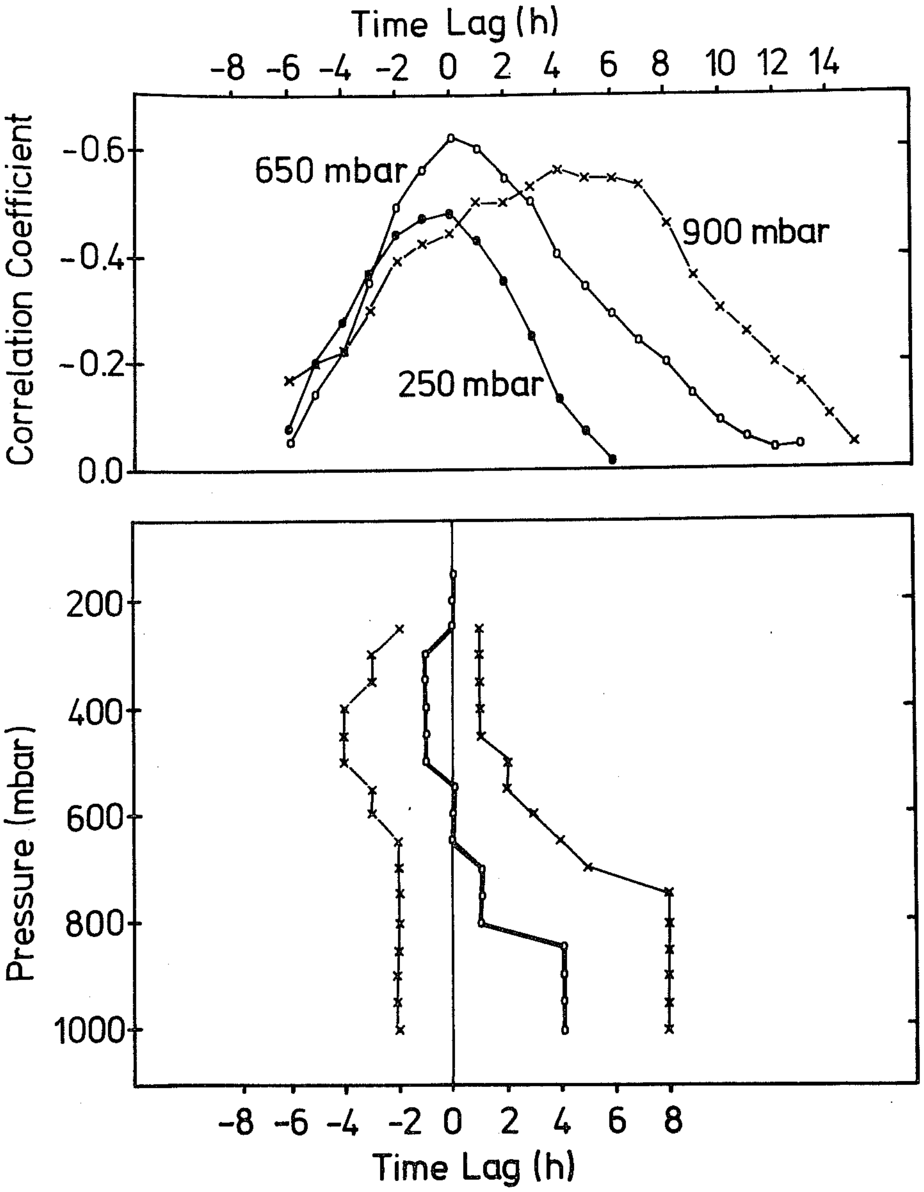

Fig. 3. Top: Correlation coefficients between rainfall and vertical velocities with different time lags at 3 levels.

Bottom: Time lag of the maximum correlation coefficients at each 50 mbar level (thin lines show the range for a significant correlation coefficient for 2σ (= standard deviation))

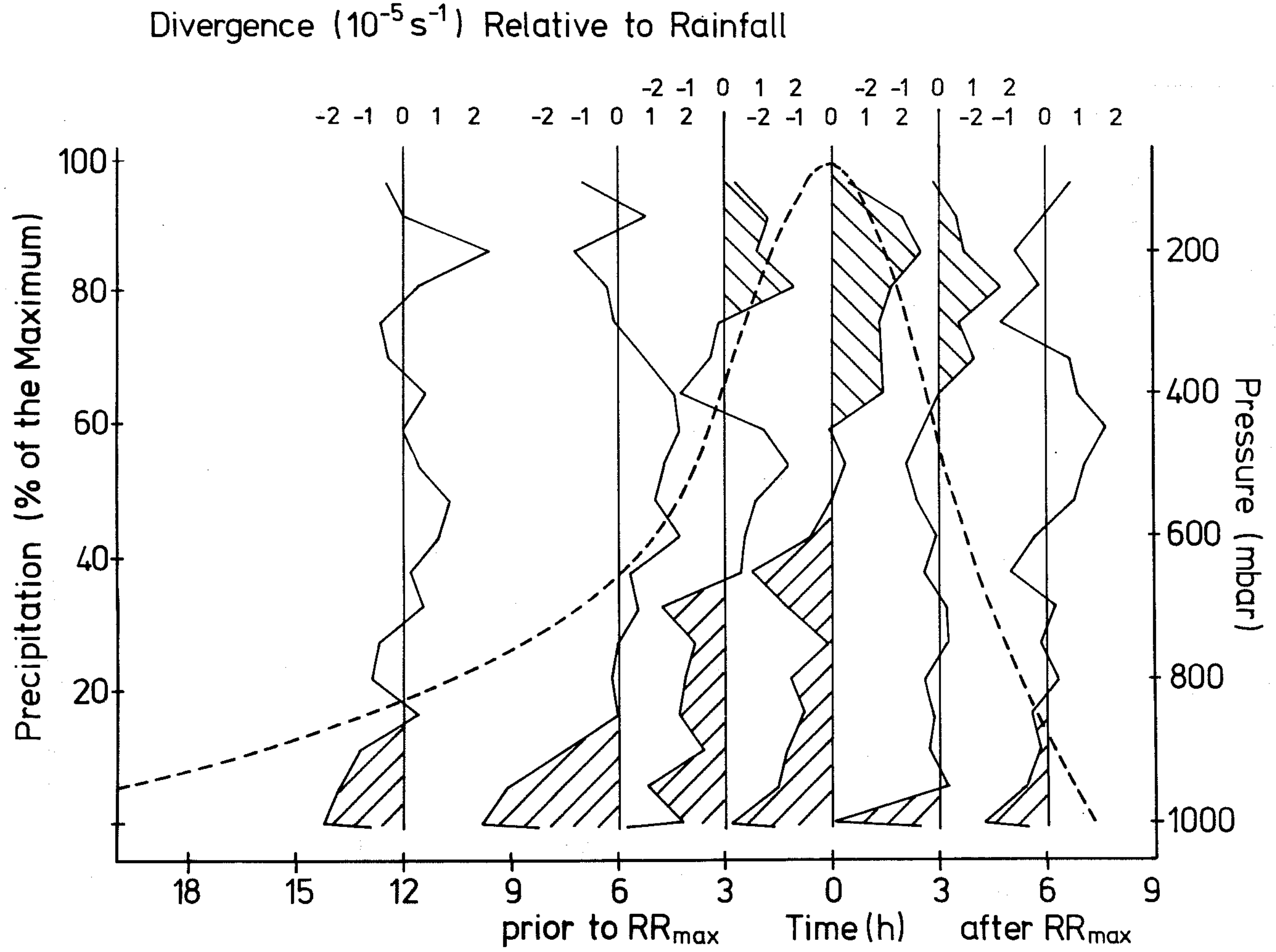

Fig. 4. Composite of the vertical divergence profiles relative to rainfall maximum (dashed line gives the course of the rainfall relative to its maximum)

4. Energy budget

In order to study the energy budget (total potential (PE), kinetic (KE) or available potential (APE) energy) the cloud mass flux distribution has to be known. The radar observations (echo top heights) onboard of RV "Planet" provide the data to derive the cloud distribution. A method was developed to calculate the mass fluxes and the properties of the up- and downdrafts. It is described in Ruprecht (1981 b). An one-dimensional cloud model for entraining and detraining clouds is used. It is assumed that each cloud contains a pair of updrafts and downdrafts, which are both related to each other. The bulk parameters of the total cloud ensemlbe are calculated and compared with the observed B-scale values as total rainfall and the apparent heat and moisture sources. The results were then used to derive the energy budget.

The kinetic energy equation for a limited region can be written as

$$\frac{\partial \overline{K}}{\partial t} = -\int_{100}^{Ps} \overline{\nabla \cdot K \mathbb{V}} \frac{dp}{g} - \int_{100}^{Ps} \frac{\partial}{\partial p} \overline{K\omega} \frac{dp}{g} - \int_{100}^{Ps} \mathbb{V} \cdot \nabla \phi \frac{dp}{g} + \int_{100}^{Ps} \overline{\mathbb{V} \cdot F} \frac{dp}{g} + \frac{1}{g} \overline{\frac{\partial Ps}{\partial t}} \overline{K}_s$$

$$= -\ \mathrm{HDK} \qquad - \mathrm{VDK} \qquad + \mathrm{GK} \qquad + \mathrm{FK} \qquad + \mathrm{PSK} \qquad (1)$$

$\overline{K} = \frac{1}{\sigma} \int_{\sigma} \int_{100}^{Ps} \frac{1}{2} (u^2+v^2) \frac{dp}{g} d\sigma'$ = mean KE averaged over the area σ of the limited region

ϕ = Geopotential

F = Friction

HDK and VDK are the horizontal and vertical divergences of the KE flux. With the assumption $\overline{K\omega}(Ps) = \overline{K\omega}(100\ \mathrm{mbar}) = 0$ we have VDK = 0. GK is the generation of KE by the cross-contour flow. PSK (time change of the surface pressure) gives the results from the exchange of differentation and integration on the left hand side of equ. 1.

The calculation show that it is very small and can be neglected here.

The total potential energy (PE = $c_v T+gz$) equation is given by

$$\frac{\partial\overline{PE}}{\partial t} = -\int_{100}^{Ps} \overline{\nabla\cdot H\,\mathbb{V}}\;\frac{dp}{g} - \int_{100}^{Ps} \frac{\partial}{\partial p}\,\overline{H\omega}\,\frac{dp}{g} + \int_{100}^{Ps} \overline{\alpha\omega}\,\frac{dp}{g} + \int \overline{Q}\,\frac{dp}{g}$$

$$- \frac{\overline{PE}_T}{g}\,\frac{\overline{d\Phi}_T}{dt} + \frac{\overline{PE}_s}{g}\,\frac{\partial\overline{p}_s}{\partial t}$$

$$= HDH \qquad - VDH \qquad - WT \qquad + GE$$

$$- PT \quad + PSP \qquad\qquad (2)$$

$H = C_pT$=Enthalpy

HDH and VDH are the horizontal and vertical divergence terms. WT is the release of PE by warm rising and cold air sinking. GE is the generation of PE by the release of latent heat and by radiation. PT results from the relation between PE and H, it is calculated with the values at the top of the limited region (100 mbar). In general it is very small thus it can be neglected as PSP. For a closed system WT equals GK but for an open system more terms are included.

Table 1 Components of the energy budget

Date	Time GMT	KE $10^3 J/m^2$	GE	WT	$HD\phi_2$	GK	HDH
					$w\ /\ m^2$		
Sept. 2	18	85	1820	6980	7036	-56	-4400
Sept. 4	18	360	145	- 698	- 669	-29	307
Sept. 5	00	227	840	4003	3949	54	-2646
	06	124	1065	2098	2039	59	- 961

$$- \int_{100}^{Ps} \overline{\mathbb{V}\cdot\nabla\phi}\, \frac{dp}{g} = - \int_{100}^{Ps} \overline{\alpha\omega}\, \frac{dp}{g} - \int_{100}^{Ps} \overline{\nabla\cdot\phi\, \mathbb{V}}\, \frac{dp}{g} - \int_{100}^{Ps} \frac{\partial}{\partial p}\, \overline{\phi\omega}\, \frac{dp}{g}$$

$$GK \quad = \quad WT \quad - \quad HD\phi \quad - \quad VD\phi \qquad (3)$$

If we again take $VD\phi = 0$, it follows from equ. (3) GK is the difference of the release of PE and the divergence of the horizontal geopotential flux. WT is directly affected by the updraft-downdraft circulation, all the other terms can be calculated by the mesoscale parameters. GK is derived from equ. (3).

Tab. 1 shows the results. The first case is for a mature stage at the rainfall maximum and the other 3 are for developing stage of a cloud cluster. Total potential energy is generated in a large amount by the release of latent heat. The term WT shows that even more is converted into other forms by the updraft-downdraft circulation. The difference is mainly balanced by an enthalpy import (HDH). Only a very small amount of WT is used to generate KE, it is exported in form of potential energy ϕ into the environment.

During the mature stage GK is negative, that means KE is reduced to export more potential energy. Fig. 5 shows the vertical profiles of the contribution of each 50 mbar layer to WT and $HD\phi$. It is seen that $WT > HD\phi$ in the lower troposphere, and the reverse is true above. That means potential energy must be transported upwards by the circulation within the cloud clusters. For the mature stage at Sept. 2 the export of geopotential is very large that the updraft-downdraft circulation cannot release enough total potential energy to supply the export and generate KE.

The total effect of the cloud ensemble and its immediate environment can be summarized in the following picture: Latent heat is released within the cloud updrafts and generates total potential energy; this energy is released by the updraft-downdraft circulation; little is consumed to increase KE, during the mature stage even a decrease of KE is found; most of the released energy is exported as potential energy into the larger environment where it is realized in the compensating sinking. Similar results are shown by Riehl (1977) for the Venezuelan rain systems.

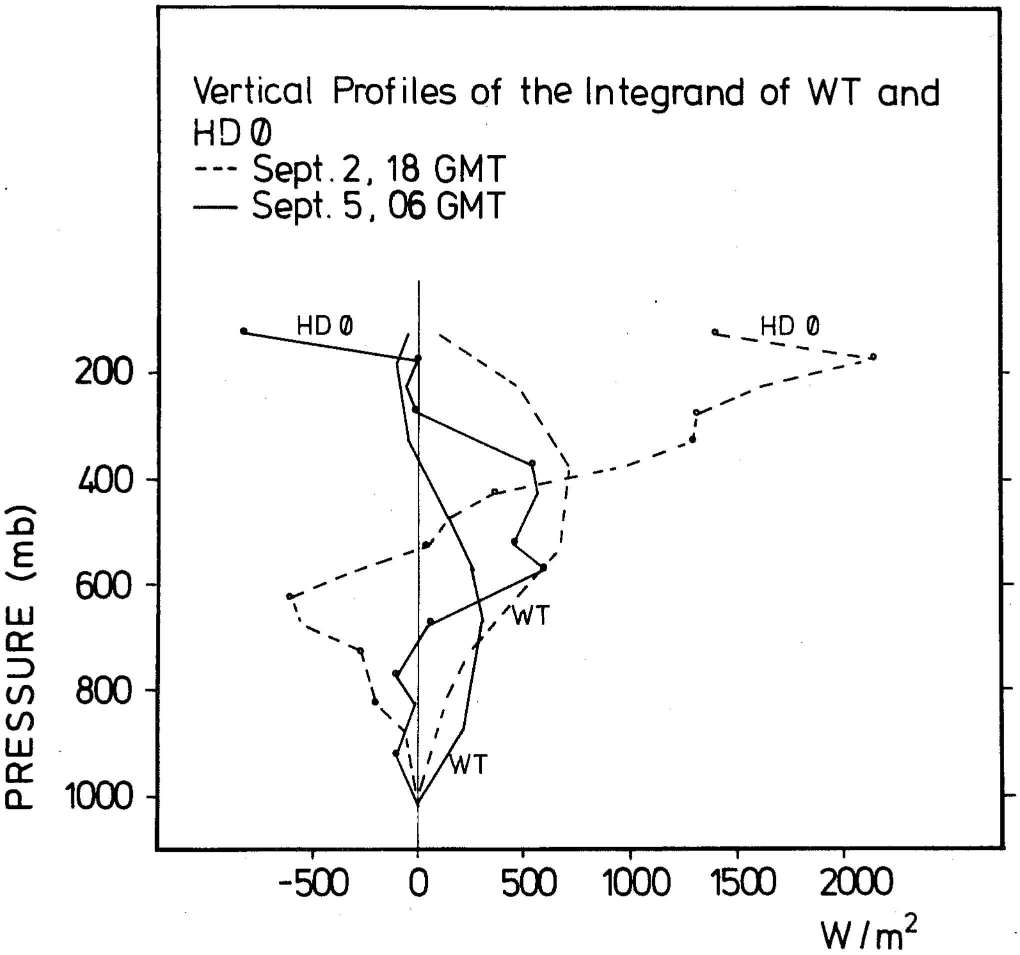

Fig. 5. Vertical profiles of the contribution of each 50 mbar layer to the WT - and HDϕ - terms

5. Conclusion

The investigation of the relation between the divergence and the rainfall shows clearly how important the knowlwdge of the vertical structure of the divergence and of the humidity fields are for an understanding of the deep cloud development. The shallow clouds transport water vapor upwards into the middle levels. Not before this region is moist enough the deep clouds can penetrate it and reach the upper troposphere. Therefore the analysis of the data must consider besides the boundary layer consitions, very carefully the middle troposphere (6oo - 4oo mbar) to provide the accurate fields for the prediction of the disturbances in the tropics.

The energy budget emphasizes the importance of the updraft-downdraft circulation. It releases the total potential energy which is generated by the release of latent heat. The main output of the cloud ensemble into its immediate environment is the flux of geopotential energy. The divergence of the flux of enthalpy and geopotential - $c_p T + \phi$ - is in the order of 2ooo W/m^2 for the developing and mature stage of the disturbances. A comparison of the total flux divergence for the latitude belt between equator and 2o°N as given by Palmen and Newton (1969) shows that 1o to 15 of such disturbances are needed at any time to provide this amount of energy for the tropical circulation.

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