THE IMPACT OF CLOUD CLUSTERS ON THE FLOW AS DERIVED FROM GATE DATA

E. Ruprecht

Institut fuer Geophysik und Meteorologie
Universitaet zu Koeln, F. R. Germany

1. INTRODUCTION

The processes in the tropics are more complex and their effects on the general circulation are more important than it was thought, before better information was available and before refinements of the numerical model were achieved. The importance of the latent heat, which is transported by the trade winds towards and released within the ITCZ, was already known long ago (e.g. v. Ficker, 1936). But what really happens within the inner tropics was not understood.

A main step forward was the hot-tower-hypothesis of Riehl and Malkus (1958). They proposed that only deep cumulonimbi (hot towers) can transport energy out of the boundary layer (source region) into the upper troposphere (sink region). They even stated that the Cb's are organized in disturbances. The latter was confirmed with the observation of the atmosphere from space about ten years later.

Satellite images revealed that the ITCZ is built up of a number of disturbances which move from E toward W, called cloud clusters. The discontinous ITCZ is one of the striking features in the tropical atmosphere. On the other side the tropical continents also play an important role for the development of convection. An estimate has shown that nearly 30 cloud clusters exist at any time.

There exists also very intensive disturbances - the tropical storms. From their investigations much was learnt about the cloud clusters. First, the diabatic heating provided by the release of latent heat was demonstrated to be the energy source of the tropical disturbances. Second, Charney and Eliassen (1964) and Ooyama (1964) introduced the CISK to explain the formation of the tropical storms. It was later demonstrated (see a review by Bates, 1977) that CISK in its general form can explain the formation of tropical disturbances in general. The application of CISK leads to the development of a disturbance of certain size within the conditionally unstable tropical troposphere because of the interaction of the low-level convergence and conditional instability. Otherwise only an overtuning occurs with large number of small convective clouds.

A low-level convergence is also necessary as a trigger mechanism to enable the air parcels to penetrate the unsaturated, stable lowest layer and to reach the conditionally unstable middle levels.

The cloud clusters, which will be discussed here, are the regions where the latent heat is released. That means we must consider them as a main, essential part of the motor which drives the general circulation.

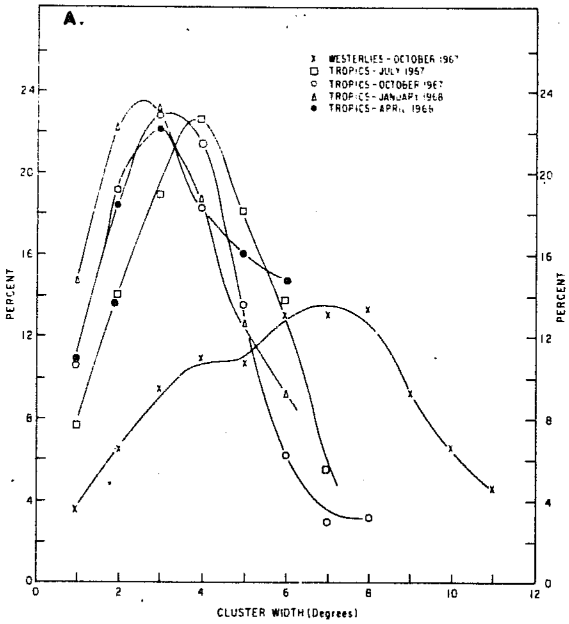

Fig. 1 Frequency distribution of cloud cluster relative to their width (after Hayden, 1970)

2. PHENOMENOLOGY OF THE CLOUD CLUSTER

Cloud clusters occur in a large variety of sizes as the statistic derived by Hayden (1970) demonstrates (Fig. 1); the prominent cluster area is 400 x 400 km^2. This was also confirmed by the tropical experiment GATE-the main goal of which was to investigate the convection and its role for the tropical disturbances which will be discussed (for a review see Houze and Betts, 1981). The life time of the cloud cluster is between some hours to days. Because the cluster intensity can be subject to large variations, that explains some of the life time differences. As the trajectories derived by Martin and Schreiner (1981) show (Fig. 2) the cloud clusters move towards the west, i.e. in the direction of the mean wind at 700 hPa. Because of their high speed (given by the inset of Fig. 2) they move against the low-level winds, an important fact for their development.

Chang (1970) also revealed that they have a periodic appearance. He concluded that the cloud cluster are associated with the easterly waves. That was partially confirmed by a composite study of Ruprecht and Gray (1976a). The zonal section of the meridional winds shows the strong S-winds E of the cloud cluster centre and weak and variable winds W of it (Fig. 3). They concluded that many individual clusters do not fit the mean pattern of a wave. There is no question that many cloud clusters are associated with a wave motion in the low and middle levels, but there is evidence that they also can occur without a wave. This seems particularly true for those over the continents. Many authors on the other side have shown that the waves receive their energy from the latent heat release (e.g. Chang, 1976; Hayashi, 1970). Thus there is a close interaction between cloud cluster and wave development.

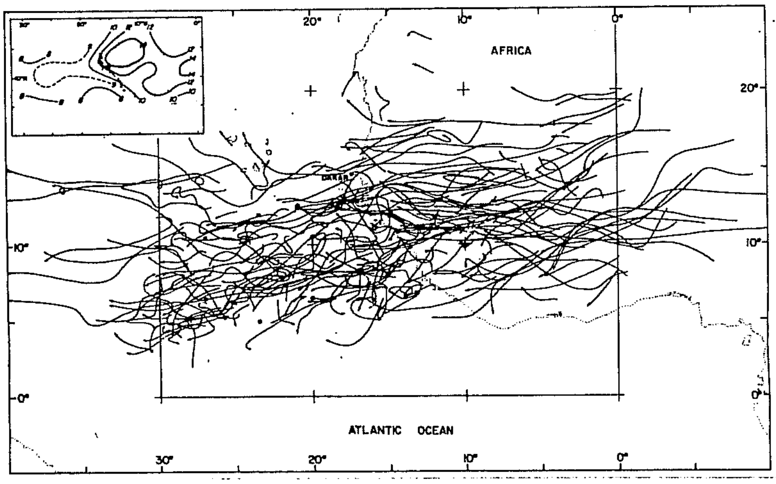

Fig. 2 Tracks of cloud clusters over the GATE area; inset in the upper left: cloud cluster speed in m/s (after Martin and Schreiner, 1981)

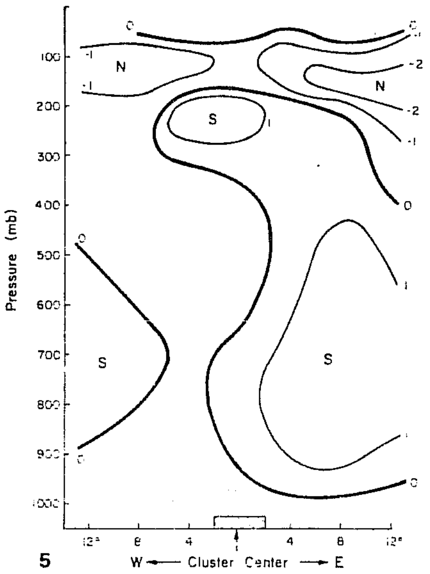

Fig. 3 Height-longitude section for a W-Pacific cloud cluster composite of the meridional winds in m/s (after Ruprecht and Gray, 1976a).

3. INTERNAL STRUCTURE

From satellite observations alone the internal structure of the cloud cluster cannot be derived. A thick cirrus anvil covers the whole area and even hides the deep convective clouds. An indirect analysis was performed by Ruprecht and Gray (1976b) using the hourly rainfall observations from W Pacific islands and atolls. The composite (Fig. 4) demonstrates the high concentration of rainfall beneath a cloud cluster; only 1 % of the area has an intensity of more than 20 mmh^{-1}. But there is also a large area of almost 40 % with light rains. That was confirmed by the observation during GATE. The cloud clusters are characterized by deep convective elements, but also by thick cloud layers between the convective clouds (e.g. Fig. 5 from Houze, 1977).

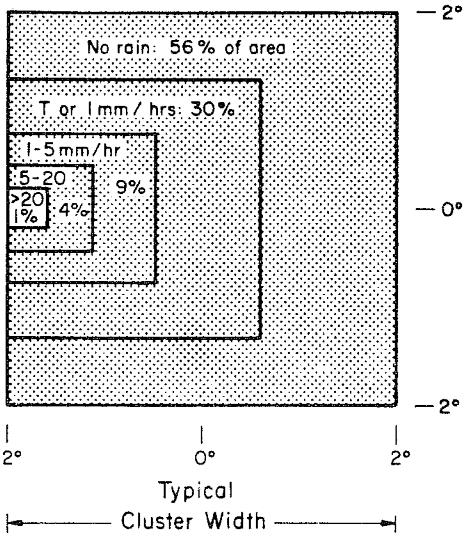

Fig. 4 Spatial rainfall distribution for a W-Pacific cloud cluster composite (after Ruprecht and Gray, 1976b).

These results also demonstrate that within the active cloud cluster exist up- and downdrafts of different scales, convective and mesoscale. The compensating subsidence, however, is <u>not</u> found within the direct environment of the convective clouds, an assumption used in diagnostic models (e.g. Yanai et al., 1973) and parameterization of cumulus convection (e.g. Arakawa and Schubert, 1974).

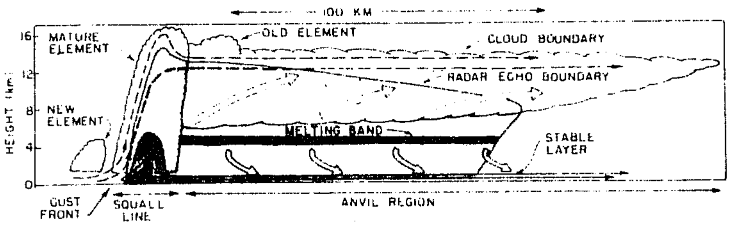

Fig. 5 Schematic cross section through a squall line system observed during GATE (after Houze, 1977).

4. SOME RESULTS OF A CLOUD CLUSTER STUDY OVER THE GATE AREA

The first ten days of Phase III of GATE (Aug. 30 - Sept. 08, 1974) are analysed to study the interaction of the cloud clusters and their environment, and to define changes of the field variables or of derived parameters which display these interactions.

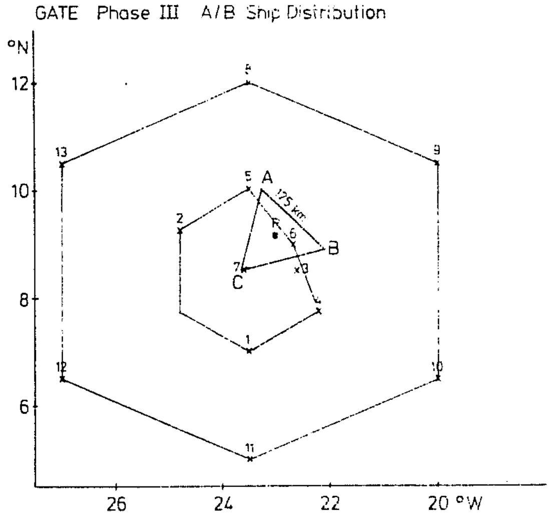

Fig. 6 Position of the triangle ABC which is used for the analysis; P = RV "Planet", numbers = other research vessels operating during GATE

The analysis of the motion (u,v), temperature (T) and humidity (q) fields is performed for a certain area which is shown at Fig. 6. A triangle of that size and location was chosen to match the area of the range of the radar on board RV "Planet" and for the use in the divergence calculation. It lies within the circle of 100 km radius with RV "Planet" in the centre. An objective analysis was applied to calculate the parameters (u,v,T,q,H=height) at each corner point (Ruprecht, 1982a). The mean field variables are defined as the average of the values at the three corner points. They represent an area (between the B- and C-scale) which includes the cloud ensemble of a cloud cluster and its immediate environment.

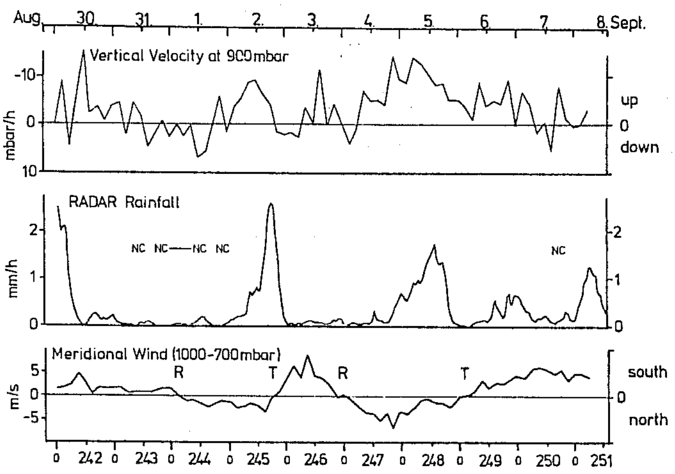

Fig. 7 Synoptic situation during the period of the analysis; T, R = trough/ ridge position of the passing through wave disturbances, NC = no cloud cluster as observed by satellite.

The synoptic situation is described in Fig. 7 by the low-level meridional winds, rainfall, satellite observations and vertical velocities. The meridional winds reveal that two and an half waves passed the area (during that period) of the type described by Thompson et al. (1979). Cloud clusters seen in the satellite images are found near the indicated trough situations (T). The maximum of rainfall and of calculated upward velocity is associated with the cloud cluster appearance.

The time-height sections of the mass divergence (Fig. 8a) and vertical velocity (Fig. 8b) show three striking features:

1. The advent of the cloud clusters is marked by a strong low-level convergence.
2. Middle levels (400-600 hPa) are characterized by divergence.
3. The maximum of the low-level convergence and of the vertical velocity is at the beginning of the period of intense rainfall.

Over the ocean, low-level convergence always implies a convergence of the water vapour transport which is needed as energy source for the cloud clusters. The vertical structure of multiple layers of convergence and divergence seems to be typical for the GATE area. It was even found in the mean Phase III profile (Thompson et al., 1979). It agrees with the occurrance of multi-layered clouds in the region as described above (see Fig. 5).

The relationship between convergence and rainfall affords some insight into the structure of the cloud cluster. The time lag (of about 6 hours) between low-level convergence and rainfall is well documented in the literature (e.g. Ulanski and Garstang, 1978; Cho and Ogura, 1974; Brümmer, 1979) and it was also found in our data (Ruprecht, 1982a).

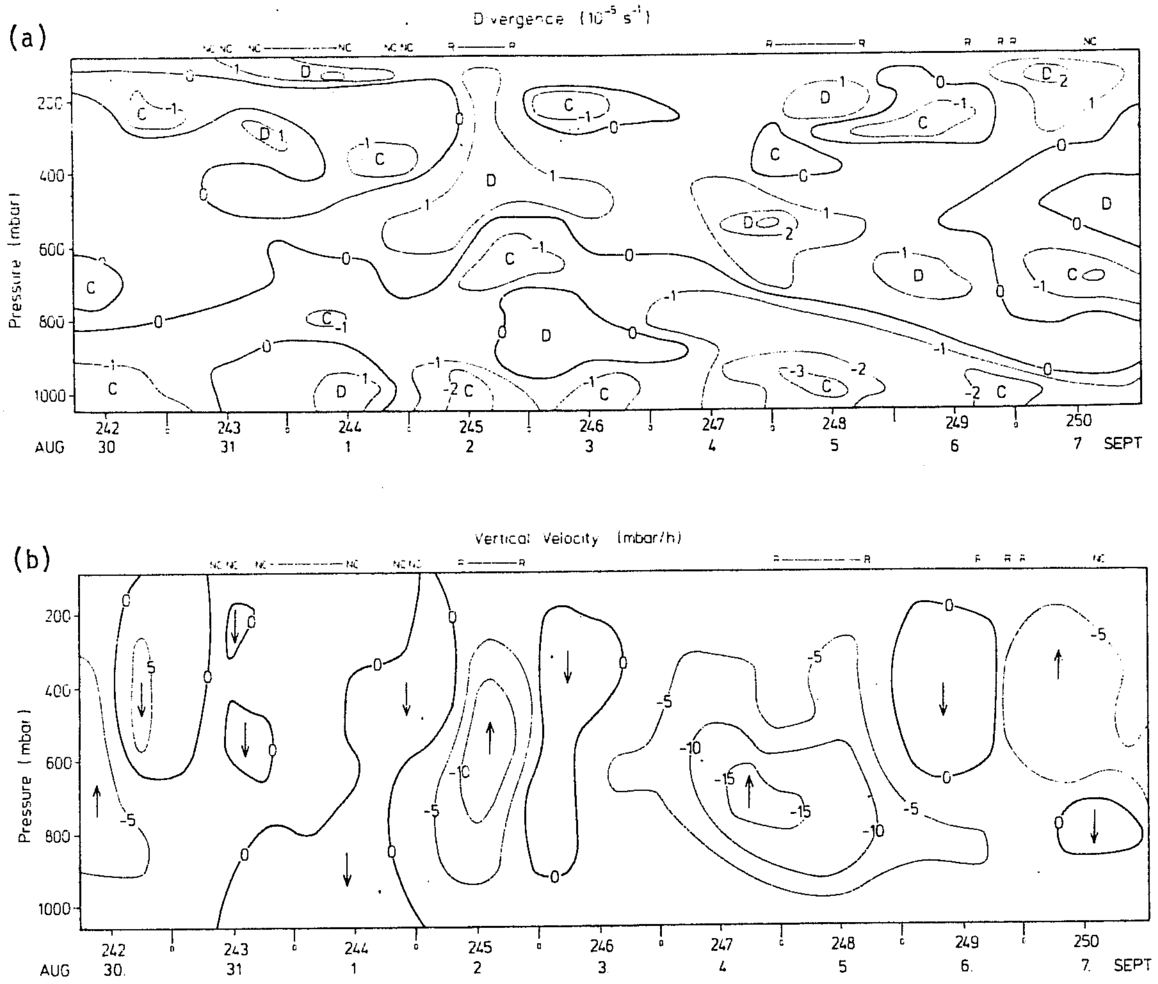

Fig. 8 Time-height sections of the divergence (a) and vertical velocity (b) calculated for the column over the triangle ABC (see Fig. 6).

A composite of the vertical divergence profiles relative to the rainfall maximum was prepared (Fig. 9) to understand what is behind this time lag. Low-level convergence occurs at all times prior and after the rainfall maximum. It attains its maximum 6 h before the rainfall maximum. At that time the outflow divergence is found in the middle troposphere between 700 and 300 hPa. It seems that the upper troposphere is not yet affected. Approaching the time of the rainfall maximum the magnitude of the low-level convergence decreases but the depth of the convergent layer increases, so does the outflow divergence in the upper troposphere (300-150 hPa). The maximum of the outflow divergence and of the rainfall occurs at the same time. Only during these situations is the 2 layer model of the divergence found which is documented for the Pacific cloud clusters by Ruprecht and Gray (1976a), but the outflow layer is much deeper over the GATE region.

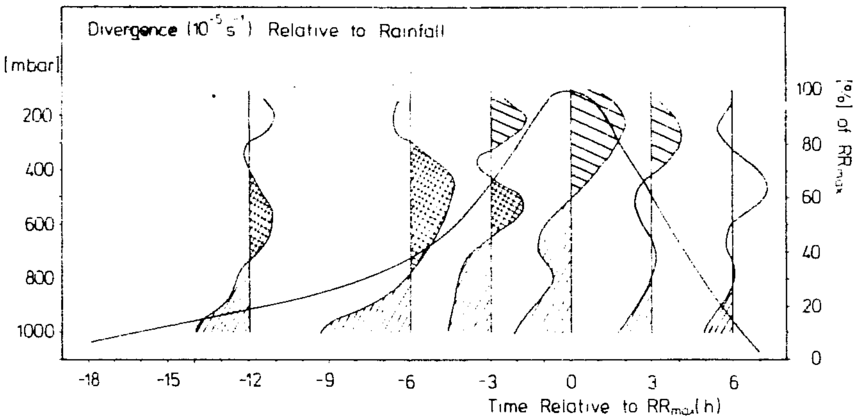

Fig.9 A composite time series of the divergence profiles relative to the rainfall maximum over the triangle ABC.

The series of these profiles confirms the hypothesis that the development of the penetrative deep cumulonimbi depends on the properties of the middle levels (Gray, 1973). The low-level convergence provides the water vapour which is fed into these middle levels, thus, the deep clouds can grow despite the entrainment of environmental air. The middle level divergence in these profiles also demonstrates the origin of the stratiform clouds within the cloud clusters. This fact is indicated in a later section.

5. A DIAGNOSTIC MODEL

In order to investigate the vertical transports by the up- and downdrafts within a cloud cluster a diagnostic model was developed (Ruprecht, 1982b). It is based on the diagnostic equation derived by Yanai et al. (1973) which can be successfully used to describe the scale interactions:

$$Q_1-Q_2-Q_R = -\frac{\partial\overline{h'\omega'}}{\partial p} \qquad (1)$$

Q_1, Q_2 are the apparent heat source and moisture sink, respectively. They are defined by the large-scale variables:

$$Q_1 = \frac{\partial\bar{s}}{\partial t} + \overline{\nabla s\mathbf{V}} + \frac{\partial\bar{s}\bar{\omega}}{\partial p} \qquad (2)$$

$s = c_pT+gz$ = dry static energy

$$Q_2 = -L\left(\frac{\partial\bar{q}}{\partial t} + \overline{\nabla q\mathbf{V}} + \frac{\partial\bar{q}\bar{\omega}}{\partial p}\right) \qquad (3)$$

q = specific humidity, L = latent heat of condensation

Q_R = radiative heating

$h = c_pT+gz+Lq$ = moist static energy

The left hand side of equation (1) contains only variables of the analyzed (large- or meso-scale) field and the right hand side the convective scale parameters. It is assumed that the "turbulent" transport h is mainly due to the convection.

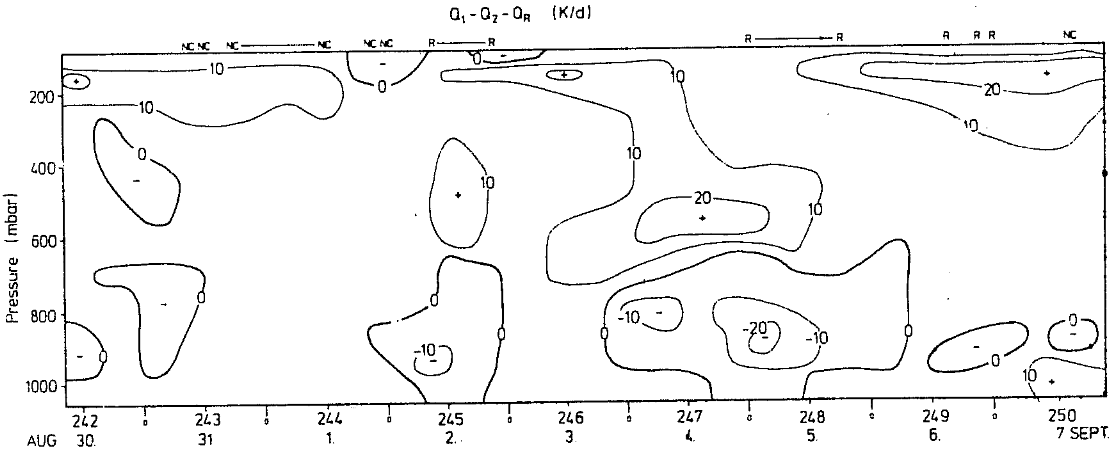

Fig. 10 Time-height section of the sum of the apparent heat and moisture sources and the radiative heating for the column over the triangle ABC.

Fig. 10 shows a time-height section of the sum of the apparent sources and sinks. Considerable magnitudes are only found in connection with the cloud clusters. With equation (1) the negative values can be interpreted as divergence of the vertical convective transport. During those periods Q_1 and Q_2 (the contribution of Q_R is in general small) have normally the same sign. In the lower troposphere $Q_2 > Q_1$ but the reverse is true at the upper levels. That means the convective moisture transport in upwards, with transport of sensible heat downwards.

A diagnostic model is applied to calculate the convective transports. The cloud spectrum which is responsible for these transport is derived from radar observations, number of echo cores and their top heights. Each echo core is assumed to be one cloud. The clouds are characterized by their entrainment rates which determine the cloud top heights and updraft temperatures and humidities. It is further assumed that not only entrainment but also detrainment occur at each level and that each updraft has as a counterpart a convective downdraft. With those assumptions, with the radar measurements, the observed rainfall, and the calculated apparent heat sources and moisture sinks, the convective transports are derived.

The results demonstrate the importance of the cloud clusters. The total mass flux out of the boundary layer by the cloud updrafts is two orders of magnitude larger in a cloud cluster case than in a situation with only shallow clouds. That means, the mass circulation within the tropics is dominated by the cloud clusters.

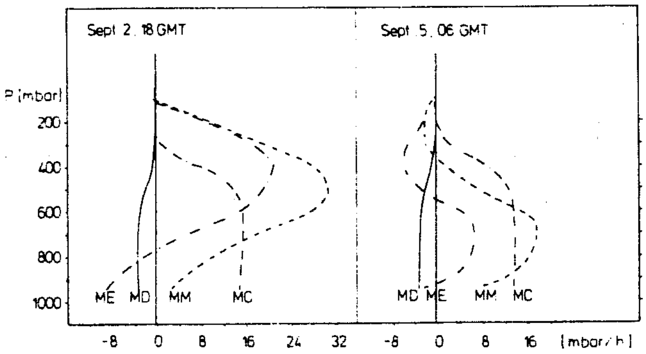

Fig. 11 Vertical profiles of the vertical mass fluxes for two situations during GATE (compare Fig. 7); MC/ MD = cloud updraft, downdraft mass flux, MM = mean mass flux (see Fig. 8), ME = mesoscale mass flux within the cloud immediate environment.

Fig. 11 reveals more details of the mass circulation. Two examples are given for different situations:
Sept. 02 18 GMT at a mature stage of a cloud cluster with maximum of rainfall;
Sept. 05 06 GMT at a developing stage of a cloud cluster with increasing rainfall. In the first case the horizontal mass flow shows an inflow below 550 hPa and an outflow above. Therefore the net mass flux increases rapidly with height. Above 725 hPa it even exceeds the cloud mass flux. Since part of the mass is transported downwards by the convective downdrafts, the meso-scale mass flux is downward below 775 hPa and upwards above. Because the inflow layer is more shallow in the second case the net mass flux reaches its maximum already at the 700 hPa level and then decreases rapidly. Thus, a meso-scale upward flux is derived for the levels between 825 and 550 hPa. The meso-scale motion is in agreement with the anvil circulation described by Leary and Houze (1979) and Zipser and Gautier (1978) (see Fig. 5).

The production of the stratiform clouds can be shown by the analysis of the hydrological budget. Besides the two cases already described, Fig. 12 shows a situation of an intense but still developing cloud cluster. For the intense cloud cluster the water vapour flux by the cloud updraft out of the inflow layer is very large. It balances or even exceeds the water vapour inflow minus precipitation. The deficit can be balanced by a downward liquid water flux (Sept. 02 18 GMT). In the early developing stage (Sept. 05 00 GMT) the upward transport by clouds is much smaller; therefore the liquid water content increases in the inflow layer.

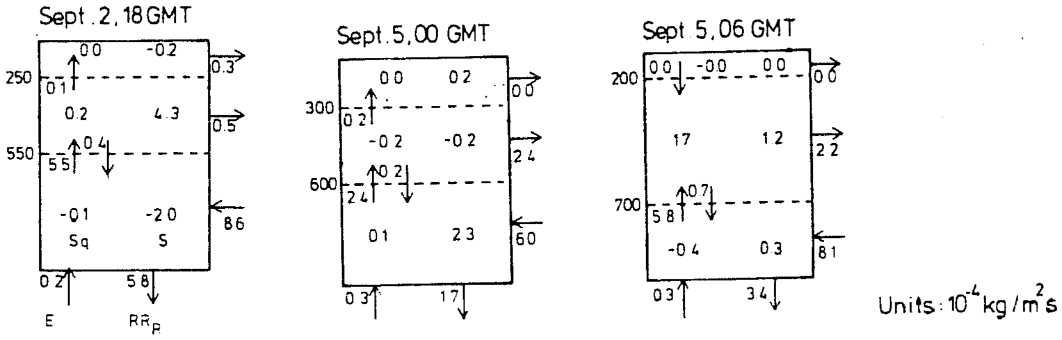

Fig. 12 Hydrological budgets of the column over the triangle ABC for the three different situations during GATE (compare Fig. 7), RR = rainfall derived from radar observations, E = evaporation calculated by the bulk formular, S, Sq = storage of liquid water/ water vapour, arrows point in the direction of the net water vapour flux.

If we assume that S gives the horizontal divergence of the liquid water transport, then the budgets reveal that in all three cases liquid water is exported into the environment and this increases the intensity of the cloud clusters at the higher levels.

6. CONCLUSION FOR THE INTERNAL CIRCULATION

Together with the conclusion discussed earlier based on Fig. 9, it follows that the clouds within the cloud clusters moisten their environment by the export of water vapour in the outflow layer and produce stratiform clouds by the export of liquid water. The level of the export for both water vapour and liquid water increases from the early developing stage of the cloud cluster.
This type of circulation derived from the mass and the hydrological budget corresponds to the results of the energy budget. Nearly all energy which is gained by the cloud cluster by the release of latent heat and by convergence of sensible heat transport is exported in the form of potential energy into the environment where it is realized in the compensating sinking.

The important finding can be summerized as follows.
The compensating subsidence occurs not in the immediate environment of the clouds; that means its warming and drying do not affect the clouds directly;
but the immediate environment is moistened by the water vapour outflow and probably cooler by re-evaporation of cloud droplets at the cloud edges and in particular beneath the layer of stratiform clouds.

7. REFERENCES

Arakawa, A. and W.H. Schubert, 1974: Interaction of a cumulus cloud ensemble with the large-scale environment.
J. Atm. Sci., 31, 674-701.

Bates, J.R., 1977: Parameterization of convective processes.
ECMWF Seminar on "The Parameterization of the Physical Processes in the Free Atmosphere", 160-229.

Brümmer, B., 1979: Boundary layer processes during the life cycle of GATE convective disturbances.
Beitr. Phys. Atm., 52, 306-330.

Chang, C.P., 1970: Westward propagating cloud patterns in the tropical Pacific as seen from time-compositing satellite photographs.
J. Atm. Sci., 27, 133-138.

Chang, C.P., 1976: Vertical structure of tropical waves maintained by internally induced cumulus heating.
J. Atm. Sci., 33, 729-739.

Charney, J.G. and A. Eliassen, 1964: On the growth of the hurricane depression.
J. Atm. Sci., 21, 68-75.

Cho, H.-R. and Y. Ogura, 1974: A relationship between cloud activity and the low-level convergence as observed in Reed-Recker's composite easterly waves.
J. Atm. Sci., 31, 2058-2065.

Ficker, von H., 1936: Die Passatinversion.
Veröffentlichung des Meteor. Instituts, Univ. Berlin, Bd.1/4, pp 33.

Gray, W.M., 1973: Cumulus convection and large-scale circulations.
Mon. Wea. Rev., 101, 839-855.

Hayashi, Y., 1970: A theory of large-scale equational waves generated by condensation heat and accelerating the zonal wind.
J. Meteor. Soc. Japan, 48, 140-160.

Hayden, C.M., 1970: An objective analysis of cloud cluster dimensions and spacing in the tropical North Pacific.
Mon. Wea. Rev., 98, 534-540.

Houze, R.A., 1977: Structure and dynamics of a tropical squall-line system.
Mon. Wea. Rev., 105, 1540-1567.

Houze, Jr. R.A. and A.K. Betts, 1981: Convection in GATE.
Rev. Geophys. Space Phys., 19, 541-576.

Leary, C.A. and R.A. Houze, 1979: Melting and evaporation of hydrometers in precipitation from the anvil clouds of deep tropical convection.
J. Atm. Sci., 36, 669-679.

Martin, D.W. and A.J. Schreiner, 1981: Characteristics of West African and East Atlantic cloud clusters: A survey from GATE.
Mon. Wea. Rev., 109, 1671-1688.

Ooyama, K., 1964: A dynamical model for the study of tropical cyclone development. Geofisica Intern. (Mexico) 4, 187-198.

Riehl, H. and J.S. Malkus, 1958: On the heat balance of the equatorial trough zone.
Geophysica (Helsinki) 6, 503-538.

Ruprecht, E. and W.M. Gray, 1976a: Analysis of satellite-observed tropical cloud clusters.
Part I: Wind and dynamic fields.
Tellus, 28, 391-413.

Ruprecht, E. and W.M. Gray, 1976b: Analysis of satellite-observed tropical cloud clusters.
Part II: Thermal, moisture and precipitation fields.
Tellus, 28, 414-426.

Ruprecht, E., 1982a: An investigation of tropical cloud clusters over the GATE area.
Part I: The environmental fields of the cloud ensembles within cloud clusters.
Beitr. Phys. Atm., 55, 61-78.

Ruprecht, E., 1982b: An investigation of tropical cloud clusters over the GATE area.
Part II: Vertical transport by cumulus and cumulonimbus drafts and energy budgets.
Beitr. Phys. Atm., 55, 85-107.

Thompson, R.M., S.W. Payne, E.E. Recker and R.J. Reed, 1979: Structure and properties of synoptic-scale wave disturbances in the intertropical convergence zone of the eastern Atlantic.
J. Atm. Sci., 36, 53-72.

Ulanski, S.L. and M. Garstang, 1978: The role of surface divergence and vorticity in the life cycle of convective rainfall.
Part I: Observations and analysis.
J. Atm. Sci., 35, 1047-1062.

Yanai, M., S. Esbensen and J.-H. Chu, 1973: Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets.
J. Atm. Sci., 30, 611-627.

Zipser, E.J. and C. Gautier, 1978: Mesoscale events within a GATE tropical depression.
Mon. Wea. Rev., 106, 789-805.