

## CLOUD AND PRECIPITATION STRUCTURE OF MESOSCALE SYSTEMS IN GATE

Robert A. Houze, Jr.  
*University of Washington*

### CLOUD CLUSTERS AND THE OBJECTIVES OF GATE

While it had been recognized before the planning of GATE that deep convection over the equatorial oceans is a primary transporter of heat from the planetary boundary layer to the upper troposphere (Riehl and Malkus, 1958), it was just becoming evident during the planning of the experiment (from accumulating satellite evidence) that this convection was concentrated in "cloud clusters"\* (Martin and Karst, 1969; Frank, 1970; Martin and Suomi, 1972). Consequently, the cloud cluster and a desire to know more about the structure and organization of the deep convection comprising it played a prominent role in the planning of the experiment (e.g., GARP Report, 1970). *The Plan for U.S. Participation in the GARP Atlantic Tropical Experiment* (National Academy of Sciences, 1971, p. 5) stated that one of the scientific objectives of GATE was "to explain the bulk properties of convective ensembles [esp. cloud clusters] in terms of their internal structure." This objective was considered to be one of the main ways of achieving the general GARP objective of parameterization of the interaction between convective and synoptic scales of motion in large-scale numerical models.

This paper reviews some of what has been learned from GATE about the structure of the clouds and precipitation comprising cloud clusters (or "mesoscale systems") and the implications of these results for parameterizing scale interaction processes in large-scale models.

### TYPES OF CLOUD CLUSTERS IN GATE

It was quickly realized from the data obtained with the geosynchronous satellite launched for GATE that two distinct categories of cloud clusters could be identified, namely, squall and nonsquall clusters (Martin, 1975; Aspliden et al., 1976; Payne and McGarry, 1977). Squall clusters are associated with squall-line disturbances of the type first described by Hamilton and Archbold (1945) and later elaborated upon by Zipser (1969),

\* A cloud cluster is defined as a group of cumulonimbus joined by a common cirrus shield (GARP Report, 1970).

Obasi (1974), and Betts *et al.* (1974). According to Payne and McGarry (1977), squall clusters are identifiable in the GATE infrared satellite imagery by their "explosive growth, high brightness and distinct and general convex shaped leading edge." The speed of this leading edge averaged  $16 \text{ m sec}^{-1}$ , or about twice the speed of propagation of synoptic-scale waves (Reed *et al.*, 1977), while the nonsquall clusters tended to retrograde slightly with respect to the large-scale waves.

#### STUDIES OF SQUALL CLUSTERS

Case studies of squall clusters observed in GATE have been made by Reed (1975), Houze (1977), Zipser (1977), and Fortune (1979). These studies show that the squall clusters in GATE had the classical structure described by Hamilton and Archbold (1945) and Zipser (1969), in which a leading, arc-shaped line of active, heavily precipitating cumulonimbus elements was followed by a more lightly precipitating anvil cloud. GATE radar, aircraft, and satellite data have allowed the above authors to describe the structure of both the leading line and the trailing anvil regions in much more detail than had been possible in previous studies. For these details, the interested reader is referred to these papers. One of the most significant findings of these studies of GATE squall-line systems regards the anvil precipitation. It has been recognized since Hamilton and Archbold's (1945) work that the anvil cloud of a squall-line system covers an extensive region. For example, they noted that, while the leading line of cumulonimbus takes about 30 min to pass overhead, the trailing anvil cloud, described as overcast altostratus with a base at an altitude of 3-4 km, takes 2-3 h to pass over. Prior to GATE, however, the amount of water falling from the anvil had not been determined. For the squall-line system that passed over the GATE area on September 4, 1974, GATE quantitative radar data showed that of the total rain that fell from the cluster as a whole, about 40 percent came from the anvil cloud (Houze, 1977). The implications of this finding will be discussed in subsequent sections.

#### STUDIES OF NONSQUALL CLUSTERS

Case studies of intense GATE nonsquall cloud clusters have been made by Zipser and Gautier (1978), Warner and Austin (1978), Leary and Houze (1979a), and Warner *et al.* (1979). These studies show (using radar data) that the deep convection in these clusters was organized on the mesoscale in a manner highly similar, in certain important respects, to the convection in squall-line clusters. Specifically, the precipitation in the nonsquall clusters was contained almost entirely in one or more mesoscale regions of continuous radar echo. Each such mesoscale feature (typically  $10^4$ - $10^5 \text{ km}^2$  in area) was composed of two distinct regions, a convective region, enclosing a fluctuating pattern of deep, heavily precipitating cores, and a stratiform region, which consisted of lighter, horizontally uniform and slowly varying precipitation falling from a middle-level cloud base. Each mesoscale feature evolved through a characteristic life

cycle, composed of an *intensifying stage*, in which the convective region developed in a region of enhanced low-level convergence, a *mature stage*, in which the stratiform region developed adjacent to the convective region from the blending together of old diffuse cells from the convective region, and a *dissipating stage*, in which new cells ceased forming in the convective region but in which the stratiform region persisted for up to 8 h after the demise of the convective region.

The structure and life cycle of the mesoscale features in nonsquall clusters strikingly resemble those of the precipitation area in the squall-line cluster, which also is composed of a convective region (namely, its leading arc-shaped line) and a stratiform region (its trailing anvil region). These similarities suggest that the squall clusters are not so anomalous as might have been expected from their appearance in satellite imagery. Instead, they appear to be especially well-defined examples of a characteristic mesoscale organization of Intertropical Convergence Zone (ITCZ) convection. The similarity of the internal structure of squall and nonsquall clusters indicates that it may be possible to use rather similar cloud models to treat both squall and nonsquall convective systems.

#### STATISTICAL STUDIES OF GATE RADAR ECHO PATTERNS

The large amount of anvil precipitation falling as stratiform rain in squall clusters, and the further appearance of stratiform precipitation in nonsquall clusters, raises the question of whether this stratiform rain contributes substantially to the total precipitation in the ITCZ or is only important in specific cloud clusters. Since weather radars detect the regions of precipitation beneath the large cirrus shields of cloud clusters, as seen in satellite pictures, radar data are particularly useful for determining the average characteristics of precipitation patterns in the cloud-cluster-dominated ITCZ. Statistical studies of GATE radar echo patterns have been made by Houze and Cheng (1977), Lopez (1978), Warner and Austin (1978), and Cheng and Houze (1979). A variety of information on such characteristics as echo areas, heights, durations, motions, number of high-intensity cores, and organization or echoes into lines has been obtained, and the reader is referred to these articles for details. The relative importance of stratiform precipitation is indicated by Cheng and Houze's (1979) result that while ~60 percent of the total rain in GATE can be directly associated with a spectrum of convective cells of various heights, the remainder of the rain, some 40 percent, falls as horizontally uniform rain in the stratiform regions of large mesoscale precipitation features in cloud clusters.

#### SUMMARY OF THE OBSERVED STRUCTURE OF CLOUD CLUSTERS

The large proportion of stratiform precipitation in cloud clusters suggests that, in addition to convective-scale updrafts and downdrafts, air motions on the scale of the stratiform rain areas may also be important in the dynamics of a cluster. To visualize the types of air motions

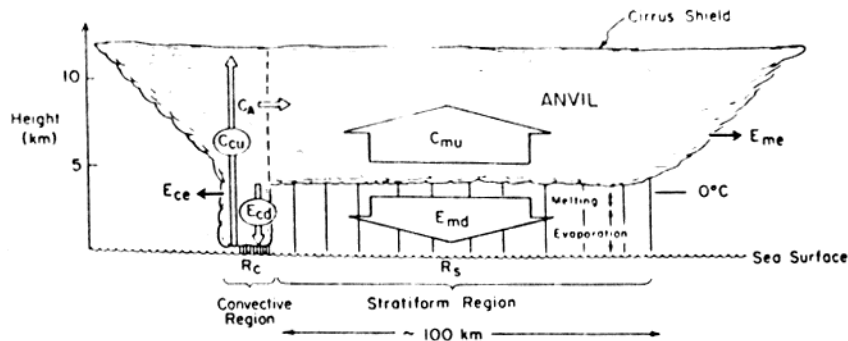


FIGURE 1 Schematic showing various components of a typical GATE cloud cluster. See text for details.

that may be involved, the structure of a typical cloud cluster, as observed in GATE, is summarized schematically in Figure 1. The figure is idealized in that it shows only one region of convective rain and one region of stratiform rain, when actually a cloud cluster can contain any number of regions of convective cells of various heights and more than one region of stratiform rain. The rain area in the diagram may be thought of as a bulk system in which the convective rain  $R_C$  is the sum of all of the convective rain produced in all the convective regions of a cloud cluster, and the stratiform rain ( $R_S$ ) is the sum of all of the rain falling in stratiform precipitation regions throughout the cluster.

Two scales of updrafts and downdrafts are shown in Figure 1. Convective-scale updrafts and downdrafts (~1-10 km in horizontal dimension) occupy the convective rain region. These are the nonhydrostatic features usually associated with cumulus-scale convection. In the stratiform precipitation region, a mesoscale downdraft (~100 km in horizontal dimension) occupies the lower troposphere below the base of the precipitating anvil cloud. This type of downdraft appears to be a basically hydrostatic feature driven by cooling from the melting and evaporation of precipitation particles in the region of stratiform precipitation below the anvil. Zipser (1969) proposed that this type of downdraft occurred below squall-line anvil clouds, and Brown (1979) has simulated the occurrence of such a downdraft in a numerical model. GATE aircraft and synoptic data show that mesoscale downdrafts occurred in the stratiform precipitation regions of both squall and nonsquall clusters (Reed, 1975; Houze, 1977; Zipser, 1977; Zipser and Gautier, 1978; Leary and Houze, 1979a; Fortune, 1979). Vertical profiles of radar reflectivity in the stratiform precipitation region (Shupiatsky, et al., 1975; Leary and Houze, 1979b) indicate that melting of precipitation particles provides strong cooling near the top of the mesoscale downdraft, possibly playing a role in its initiation, while evaporation provides cooling throughout the remainder of the layer of rainfall below the base of the anvil. Although there are few direct data to verify it, it is also possible that a mesoscale updraft (~100 km in horizontal dimension) occupies the anvil cloud itself, directly above the mesoscale downdraft. Such a feature occurred in Brown's (1979) numerical model. It is a hydrostatic circulation feature, thermally driven by condensation heating. Observations consistent with (but not proving the

existence of) such a mesoscale updraft in GATE cloud clusters include (a) the large amount of stratiform rain falling from anvils (Houze, 1977; Cheng and Houze, 1979); (b) divergent and anticyclonic 200-mbar level outflow centered in anvil cloud regions (Houze, 1977; Suchman and Martin, 1976; Leary, 1979; Fortune, 1979); (c) long persistent lifetimes of mesoscale rain areas after they reach their dissipating stage, in which they consist almost entirely of stratiform precipitation (Leary and Houze, 1979a); (d) indications that rimed ice particles (and, hence, liquid water and upward motion) existed in anvils; (e) average upward motion on the resolvable scale of rawinsonde data centered on the anvil cloud of a squall-line cluster (Ogura *et al.*, 1979).

#### IMPLICATIONS OF THE OBSERVED STRUCTURE OF CLOUD CLUSTERS FOR LARGE-SCALE MODELING

Possible implications for the incorporation of the effects of convection in cloud clusters into numerical models of large-scale flow patterns can be seen by considering the budget of condensed water in the idealized GATE cloud cluster in Figure 1. There are two sources of condensate for the cluster:  $C_{cu}$ , the mass of water condensed in convective-scale updrafts, and  $C_{mu}$ , the mass of water condensed in the mesoscale updraft. The disposition of  $C_{cu}$  and  $C_{mu}$  is indicated schematically in the figure and mathematically by

$$C_{cu} = R_c + E_{cd} + E_{ce} + C_A \quad (1)$$

and

$$C_{mu} + C_A = R_s + E_{md} + E_{me}, \quad (2)$$

where  $R_c$  is the part of  $C_{cu}$  that reaches the surface as precipitation in the convective rain region,  $E_{cd}$  is re-evaporated in convective downdrafts,  $E_{ce}$  is re-evaporated in the large-scale environment, and  $C_A$  is the portion of  $C_{cu}$  that is incorporated into the stratiform region, either by being detrained, that is, carried horizontally into the anvil cloud by air flowing out of convective cells, or by being left aloft by dying cells, which, upon ending their periods as active convective entities, blend into the anvil cloud.  $R_s$  is the total mass of water falling from the anvil cloud and reaching the surface as stratiform rain,  $E_{md}$  is the amount of water falling from the anvil cloud that is evaporated in the mesoscale downdraft, and  $E_{me}$  is moisture from the anvil cloud that is re-evaporated in the large-scale environment.

Equations (1) and (2) express the water budgets of the convective and stratiform regions, respectively, with sources of condensate on their left-hand sides and sinks on their right-hand sides. Since  $C_A$  is a sink for the convective region but a source for the stratiform region, it appears on the right of Eq. (1) and the left of Eq. (2). Here we focus on the stratiform region by considering Eq. (2).

The GATE observations, summarized in previous sections, indicate that the stratiform rain  $R_s$  is not small, either in specific cloud clusters

or on average. Furthermore, there is evidence of considerable mesoscale downdraft evaporation  $E_{md}$ . Consequently, the combined source in Eq. (2),  $C_{mu} + C_A$ , must also be large. A question that remains, though, is, what are the *relative* contributions of  $C_{mu}$  and  $C_A$  to this combined source?

Most previous diagnostic methods and parameterization schemes for determining the properties of tropical convection have either explicitly or implicitly assumed that

$$C_{mu} = 0. \quad (3)$$

Clearly, this is an extreme case, which deems *a priori* that mesoscale updrafts, which would give rise to a finite  $C_{mu}$ , do not exist. Instead, all the burden of supplying the sinks of condensed moisture in the stratiform region is placed on  $C_A$ , the only other source of condensate for this region. That is, all the sinks of condensate in the stratiform region are required to be supplied by water that was condensed externally to the stratiform region in convective cells.

Previous diagnostic and parameterization studies (except for the recent work of Johnson, 1979) have further assumed that

$$E_{md} = 0, \quad (4)$$

which specifies *a priori* that mesoscale downdrafts do not exist.

The requirements that mesoscale updrafts and downdrafts be zero, imposed by the assumptions Eqs. (3) and (4), prevent the role of mesoscale updrafts and downdrafts in large-scale fluxes of mass, heat, and other quantities to be diagnosed or parameterized. Instead, convective updrafts and downdrafts are required to account for fluxes actually accomplished by the mesoscale motions. If the mesoscale motions are significant, as is suggested by GATE observations, substantial errors may be made in diagnoses and parameterizations that do not include them.

Leary and Houze (1978; 1979c) calculated the contributions to large-scale mass and heat fluxes of an idealized cloud cluster of the type shown in Figure 1. They considered various water budgets, including cases in which  $C_{mu}$  and  $E_{md}$  were allowed to be nonzero. In these cases, the mesoscale updraft and downdraft were found to contribute significantly to the large-scale fluxes of mass and heat, and the vertical profiles of the fluxes were substantially different from those of the cases given by Eqs. (3) and (4).

## CONCLUSIONS

Cloud clusters in GATE have been found to have a characteristic mesoscale organization, in which part of the precipitation from the cluster falls directly from deep convective cells and part falls as horizontally uniform rain from a stratiform anvil cloud. A mesoscale downdraft occurs in the stratiform precipitation region below the middle level base of the anvil cloud. Melting and evaporation of precipitation particles in the stratiform region cool the downdraft. A mesoscale updraft may occur in the anvil cloud, directly above the downdraft. The mesoscale updraft and downdraft

may contribute significant fluxes of mass and heat to the large-scale budgets of these quantities, and, hence, they may have to be taken into account along with convective-scale updrafts and downdrafts in assessing the role of tropical convection in models of large-scale circulation patterns.

#### ACKNOWLEDGMENT

This work is sponsored by the Global Atmospheric Research Program, Division of Atmospheric Sciences, National Science Foundation, and the GATE Project Office, National Oceanic and Atmospheric Administration, Grant ATM78-16859.

#### REFERENCES

- Aspliden, C. I., Y. Tourre, and J. B. Savine (1976). Some climatological aspects of west African disturbance lines during GATE. *Mon. Wea. Rev.* 104, 1029-1035.
- Betts, A. K., R. W. Grover, and M. W. Moncrieff (1976). Structure and motion of tropical squall-lines over Venezuela. *Quart. J. R. Meteorol. Soc.* 102, 395-404.
- Brown, J. M. (1979). Mesoscale unsaturated downdrafts driven by rainfall evaporation: a numerical study. *J. Atmos. Sci.* 36, 313-338.
- Cheng, C.-P., and R. A. Houze, Jr. (1979). The distribution of convective and mesoscale precipitation in GATE radar echo patterns. *Mon. Wea. Rev.*, to be published.
- Fortune, M. (1979). Properties of African squall lines inferred from time-lapse satellite imagery. Submitted for publication in *Mon. Wea. Rev.*
- Frank, N. L. (1970). Atlantic tropical systems of 1969. *Mon. Wea. Rev.* 98, 307-314.
- GARP Report (1970). *The Planning of GARP Tropical Experiments*. Publ. Ser. No. 4, WMO, Geneva, 78 pp.
- Hamilton, R. A., and J. W. Archbold (1945). Meteorology of Nigeria and adjacent territory. *Quart. J. R. Meteorol. Soc.* 71, 231-262.
- Houze, R. A., Jr. (1977). Structure and dynamics of a tropical squall-line system. *Mon. Wea. Rev.* 105, 1540-1567.
- Houze, R. A., Jr., and C.-P. Cheng (1977). Radar characteristics of tropical convection observed during GATE: Mean properties and trends over the summer season. *Mon. Wea. Rev.* 105, 964-980.
- Johnson, R. H. (1979). A diagnostic model for cloud population properties that includes effects of convective-scale and mesoscale downdrafts. Submitted to *J. Atmos. Sci.*
- Leary, C. A. (1979). Behavior of the wind field in the vicinity of a cloud cluster in the Intertropical Convergence Zone. *J. Atmos. Sci.* 36, 631-639.
- Leary, C. A., and R. A. Houze, Jr. (1978). Mesoscale vertical air motions in intense tropical convection. *Preprints, Conf. on Cloud Phys. and Atmos. Meteorol. Soc.*, pp. 435-442.

- Leary, C. A., and R. A. Houze, Jr. (1979a). The structure and evolution of convection in a tropical cloud cluster. *J. Atmos. Sci.* 36, 437-457.
- Leary, C. A., and R. A. Houze, Jr. (1979b). Melting and evaporation of hydrometeors in precipitation from the anvil clouds of deep tropical convection. *J. Atmos. Sci.* 36, 669-679.
- Leary, C. A., and R. A. Houze, Jr. (1979c). Cloud mass and heat fluxes over tropical oceans: the role of mesoscale motions in intense convective systems. In preparation.
- López, R. E. (1978). Internal structure and development processes of C-scale aggregates of cumulus clouds. *Mon. Wea. Rev.* 106, 1488-1494.
- Martin, D. W. (1975). Characteristics of West African and Atlantic cloud clusters based on satellite data. *GATE Rep. No. 14, Vol. 1*, WMO, Geneva, pp. 182-190.
- Martin, D. W., and O. Karst (1969). A census of cloud systems over the tropical Pacific. *Studies in Atmospheric Energetics Based on Aerospace Probing, Ann. Report, 1968*, Space Science and Engineering Center, U. of Wisconsin.
- Martin, D. W., and V. E. Suomi (1972). A satellite study of cloud clusters over the tropical North Atlantic Ocean. *Bull. Am. Meteorol. Soc.* 53, 135-156.
- National Academy of Sciences (1971). *Plan for U.S. Participation in the GARP Atlantic Tropical Experiment*. Report of the Ad Hoc Tropical Task Group to the U.S. Committee for the Global Atmospheric Research Program, National Research Council, Washington, D.C., 25 pp.
- Obasi, G. O. (1974). The environmental structure of the atmosphere near West African disturbance lines. Preprints Int. Tropical Meteorology Meeting, Nairobi, Kenya, Part II, Am. Meteorol. Soc., pp. 62-66.
- Ogura, Y., Y.-C. Chen, J. Russell, and S.-T. Soong (1979). On the formation of organized convective systems observed over the eastern Atlantic. *Mon. Wea. Rev.* 107, 426-441.
- Payne, S. W., and M. M. McGarry (1977). The relationship of satellite inferred convective activity to easterly waves over West Africa and the adjacent ocean during Phase III of GATE. *Mon. Wea. Rev.* 105, 413-420.
- Reed, R. J. (1975). An example of a squall line in the B-scale network. *GATE Rep. No. 14, Vol. 1*, WMO, Geneva, pp. 217-222.
- Reed, R. J., D. C. Norquist, and E. E. Recker (1977). The structure and properties of African wave disturbances as observed during Phase III of GATE. *Mon. Wea. Rev.* 105, 317-333.
- Riehl, H., and J. S. Malkus (1958). On the heat balance in the equatorial trough zone. *Geophysica* 6, 503-538.
- Shupiatsky, A. B., A. J. Korotov, V. D. Menshenin, R. S. Pastushkov, and M. Jovasevic (1975). Radar investigation of evolution of clouds in the Eastern Atlantic. *GATE Rep. No. 14, Vol. 1*, WMO, Geneva, pp. 177-187.
- Suchman, D., and D. W. Martin (1976). Wind sets from SMS images: an assessment of quality for GATE. *J. Appl. Meteorol.* 15, 1265-1278.

- Warner, C., and G. L. Austin (1978). Statistics of radar echoes on day 261 of GATE. *Mon. Wea. Rev.* 106, 983-994.
- Warner, C., J. Simpson, G. van H. lvoirt, D. W. Martin, D. Suchman, and G. L. Austin (1979). Deep convection on day 261 of GATE. Submitted to *Mon. Wea. Rev.*
- Zipser, E. J. (1969). The role of organized unsaturated convective downdrafts in the structure and rapid decay of an equatorial disturbance. *J. Appl. Meteorol.* 8, 799-814.
- Zipser, E. J. (1977). Mesoscale and convective-scale downdrafts as distinct components of squall-line circulation. *Mon. Wea. Rev.* 105, 1568-1589.
- Zipser, E. J., and C. Gautier (1978). Mesoscale events within a GATE tropical depression. *Mon. Wea. Rev.* 106, 789-805.

#### DISCUSSION

A. Betts, *Rapporteur*

Results were presented (Ogura) showing that an Oklahoma squall line had a similar structure to squall lines in GATE: both the sloping updraft and downdraft, apparent conservation of  $u, v$  momentum from inflow through updraft to the outflow, and a heavy rain area moving with the system.

The discussion of the GATE squall and nonsquall mesosystems centered on the mechanism of maintenance of the radiative forcing of the thick upper-level stratiform cloud layer through the cooling of the layer at night, and the absorption of shortwave radiation during the daylight hours was discussed as a possible forcing mechanism. It was pointed out that the hydrostatic model of Brown (1979) produces explicit mesoscale ascent above mesoscale descent without radiative forcing. The observations show a sloping system on the mesoscale with condensation heating and freezing generally above the zones of melting and evaporation. The long lifetime of stratiform precipitation over ~100 km does indicate continual generation of new condensate.

Although both squall and nonsquall systems have broad similarities, it is not yet clear what differences exist in their dynamic structure, nor whether mesoscale and convective scale need be distinguished in parameterization schemes. More study of the mesoscale dynamics is needed. It is clear though that only a few mesoscale systems at most are responsible for the mass-transport diagnosed from the A/B-scale fields.