

THE WATER BUDGET OF A TROPICAL SQUALL-LINE SYSTEM

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1. INTRODUCTION

Although tropical squall lines are characterized by intense cumulonimbus cells, another important feature occurs on a horizontal scale of 100-200 km in association with the deep convection. This feature, referred to as the "anvil," is a precipitating stratiform cloud with a middle-level base that extends to the rear of the line of cells (Fig. 1). This extensive trailing stratiform cloud was first noted by Hamilton and Archbold (1945), who commented on the persistence of rain well after the passage of the disturbance line. Zipser (1969, 1977) showed that a mesoscale unsaturated downdraft occurred below the base of the anvil. Houze (1977) confirmed this finding and showed that the total (area-integrated) anvil rain (R_m) can be a significant fraction (40% in his case) of the total disturbance rainfall. Using a mesoscale numerical model, Brown (1979) showed that a mesoscale updraft occurs in the anvil, above the mesoscale downdraft.

From these studies of tropical squall line structure, the qualitative model of squall-line air motions shown in Fig. 1 was derived by Leary and Houze (1980, hereafter referred to as LH). The important question that arises is: How important are the different vertical air motion features shown in the figure (i.e., the convective cell updrafts and downdrafts and the mesoscale anvil updraft and downdraft) in relation to each other?

LH approached this problem by investigating the water budget of the squall system. The components of the budget are indicated symbolically in Fig. 1 and are related mathematically by

$$R_c = C_u - E_{cd} - E_{ce} - C_A \quad (1)$$

and

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

where R_c is the mass of rain from the squall line, R_m is the total stratiform rain from the anvil, C_u is the mass of water condensed in the updrafts of convective cells, E_{cd} is the evaporation in convective downdrafts, C_{mu} is the condensation in the mesoscale updraft, E_{md} is evaporation in the mesoscale downdraft, E_{ce} is the portion of the convective cell condensate that is evaporated into environmental air flowing through the line between cells, E_{me} is the amount of anvil condensate that flows out of the anvil to evaporate in the large-scale environment, and C_A is the amount of condensate transferred from convective cells to the anvil, either by detrainment or by discrete squall propagation, during which new cells systematically form ahead of the existing squall line while old cells weaken and blend into the anvil.

LH had no measure of the relative importance of the various terms in the water budget. Instead, they identified three hypothetical combinations of water budget parameters in Fig. 1 and Eqs. (1) and (2) covering a reasonable range of possibilities. Significantly different vertical mass and heat fluxes were found to be associated with the squall system depending on which combination was assumed. In the present paper, we derive the water budget parameters of a tropical squall-line system from data and compare the results with the three hypothetical budgets of LH.

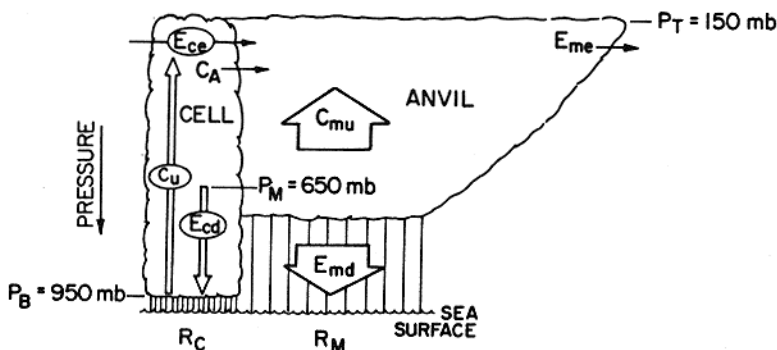


Figure 1. Schematic diagram of idealized squall system water budget. Symbols defined in text. Adapted from Leary and Houze (1980).

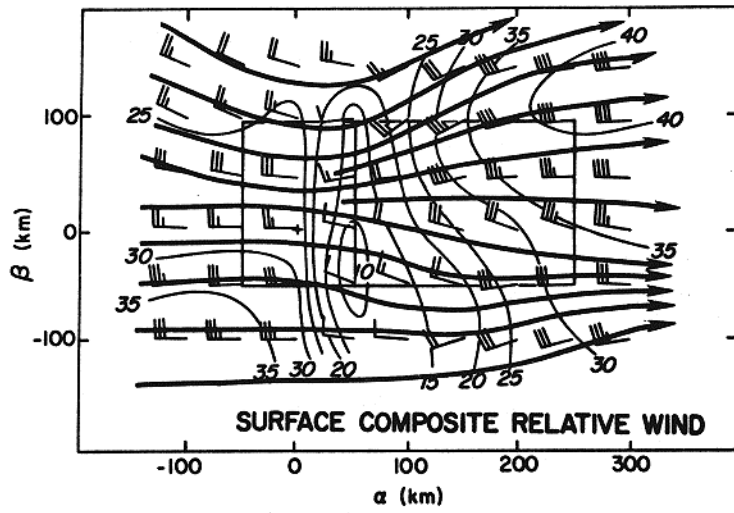


Figure 2. Composite relative surface winds with streamline and isotach analysis. The line $\alpha = 0$ is the location of the squall line. Solid contours indicate wind speed in knots. Full wind barb is for 5 kt (or 2.5 m s^{-1}). Box to the left is the squall-line region and box to the right is the anvil region.

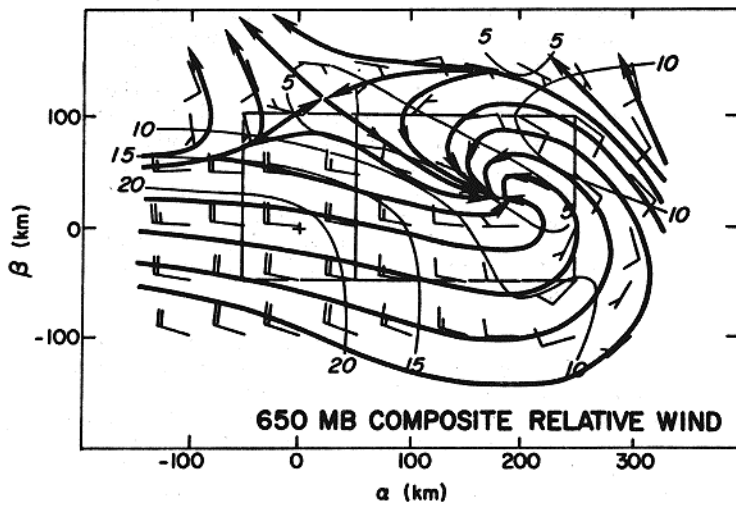


Figure 3. Same as Fig. 2, for 650 mb.

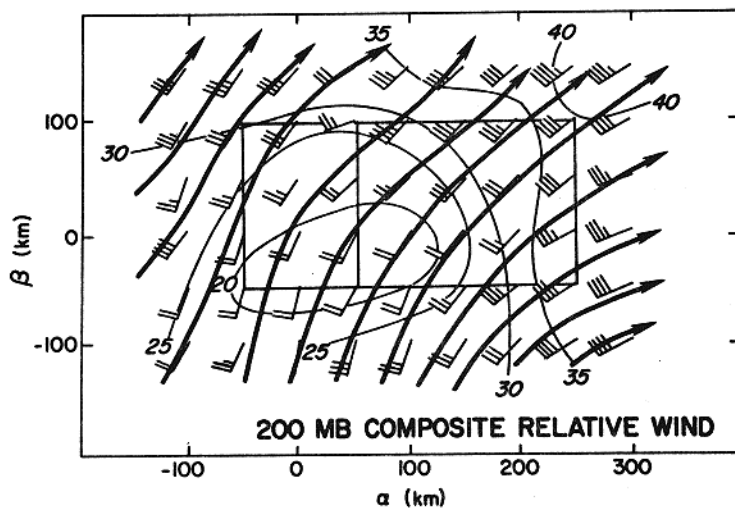


Figure 4. Same as Fig. 2, for 200 mb.

2. DERIVATION OF SQUALL-LINE AIR MOTIONS FROM DATA

To obtain the vertical air motions in a squall system, we have composited rawinsonde data with respect to the radar echo pattern of a squall line observed on 12 September 1974 during the Global Atmospheric Research Program's Atlantic Tropical Experiment (GATE). This composite analysis is described in a forthcoming paper (Gamache and Houze, 1981) and will be only briefly summarized here.

Rawinsonde observations obtained over a 9h period were located in relation to the moving squall line, which was tracked through the GATE radar network [see Hudlow et al. (1980) for a detailed description of the GATE weather radar program]. Relative wind patterns, such as those shown for three levels in Figs. 2-4, were obtained from the composite wind patterns by subtracting the mean motion of the squall system from the observed winds. In Figs. 2-4, the motion of the system is parallel to the α -axis, directed from right to left. The squall line is located along $\alpha=0$. The smaller rectangle centered on $\alpha=0$ is referred to as the squall-line region. It encloses the region shown by radar to be composed of convective cells during the time period of the composite. The larger rectangle, between $\alpha=50$ and 250 km, is referred to as the anvil region. It is the region shown by radar to be composed of stratiform (i.e., anvil) precipitation during the time period of the composite.

The three composite wind maps in Figs. 2-4 show that the relative flow was into the squall system from the front at all levels and out the rear at all levels, except near 650 mb, where a cyclonic vortex occurred in the relative flow. Inflow from the front at all levels is typical for tropical squall lines and is envisaged to occur by the incoming air flowing around and between the individual cumulonimbus cells or towers in the squall-line region [see discussions by Houze (1977) and Zipser (1977)]. The surface flow shown by Fig. 2 was convergent in the squall-line region and divergent in the anvil region. At 650 mb, (Fig. 3) the flow was nearly nondivergent in the squall-line region but convergent in the anvil region. This mid-level convergence in the anvil region fed the mesoscale anvil updraft and downdraft (cf. Fig. 1). At the 200 mb level (Fig. 4), the flow was divergent over both the squall-line and anvil regions.

The average divergences in the squall-line and anvil regions, obtained by taking line integrals of the normal outflow around the squall and anvil rectangles at each level, were integrated vertically to obtain the vertical velocity profiles in Fig. 5. In the anvil profiles the mesoscale updraft is evident above 650 mb, with the mesoscale downdraft below. Net upward motion occurred at all levels in the squall region. In the lower troposphere, this net upward motion was the difference between convective cell updraft and downdraft motions, as shown schematically in Fig. 1. In Fig. 5, the squall updraft and downdraft motions were obtained by assuming that any convergence in the squall-line region below the 900 mb level fed convective

updrafts while convergence between 900 and 650 mb fed convective downdrafts.

From the map analyses at various levels it was possible further to construct vertical cross sections of the vertical velocity in the anvil region. The cross section in Fig. 6 runs from the front (low values of α) to the rear (high values of α) of the anvil region rectangle along the line defined by $\beta=25$ km in Figs. 2-4. The general upward motion of the mesoscale updraft is seen aloft with the mesoscale downdraft motion below.

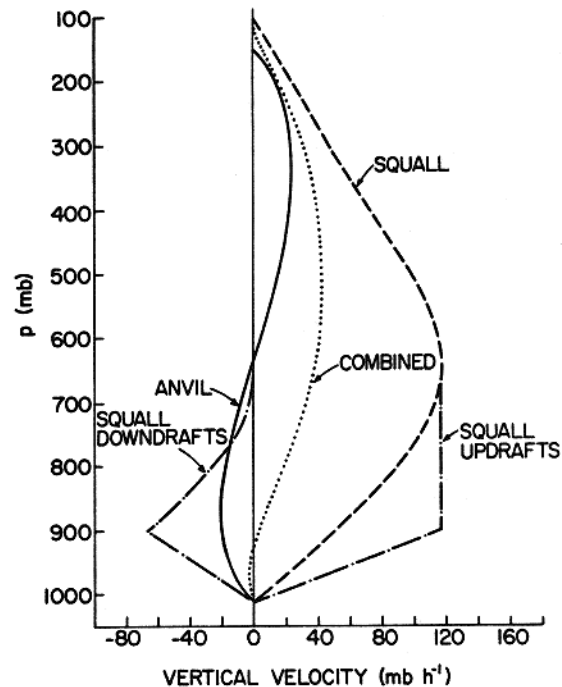


Figure 5. Average vertical velocity (w) for the squall-line (dashed), anvil (solid), and combined (dotted) regions, and for the squall-line region updrafts and downdrafts.

3. DETERMINATION OF WATER BUDGET PARAMETERS FOR THE SQUALL-LINE AND ANVIL REGIONS

3.1 General Approach

In Fig. 1 and Eqs. (1) and (2), there are nine water budget terms. In this paper, eight of these terms are determined from the composite data, while one (C_A) is determined as a residual. Since C_A appears in both (1) and (2), two estimates of C_A are obtained.

3.2 Computation of Convective Cell Condensation and Evaporation

The vertical motion profiles for squall updrafts and downdrafts in Fig. 5 are used to compute the convective cell condensation C_u and evaporation E_{cd} that appear in Eq. (1). The condensate produced in squall-line updrafts, neglecting entrainment effects, is given by

$$C_u = -\frac{A_s \tau}{g} \int_{P_T}^{P_B} [\omega_{su}(p) \frac{\partial q_u}{\partial p}] dp, \quad (3)$$

and the evaporation in squall-line downdrafts is given by

$$E_{cd} = \frac{A_s \tau}{g} \int_{P_{TD}}^{P_B} [\omega_{sd}(p) \frac{\partial q_d}{\partial p}] dp, \quad (4)$$

where $\omega_{su}(p)$ and $\omega_{sd}(p)$ are the squall updraft and downdraft vertical velocities (in pressure coordinates) from Fig. 5, p is pressure, B refers to cell base, T refers to cell top (100 mb), TD refers to the top of the downdrafts (650 mb), q_u and q_d are the specific humidities in the squall updrafts and downdrafts, respectively, A_s is the area covered by the squall-line rectangle, τ is the time period of the composite (9 h) and g is the gravitational acceleration. The mixing ratios q_u and q_d are obtained by assuming the convective cell updrafts and downdrafts are saturated with lapse rates given by moist adiabats corresponding in the case of the updrafts to the moist static energy of the pre-squall air below 950 mb and in the case of the downdrafts to the moist static energy of the pre-squall 850 mb air.

3.3 Computation of Anvil Condensation and Evaporation

To compute the anvil condensation C_{mu} and evaporation E_{md} that appear in Eq. (2), the anvil region rectangle (cf. Figs. 2-4) is subdivided into 50 km x 50 km horizontal grid squares. Each grid square defines a vertical column within which condensation C_{mu} and evaporation E_{md} are then obtained by integrating vertically and then adding the results for all the vertical columns. This procedure allows the horizontal variation of the height of the base of the anvil clouds (defined by $\omega = 0$ in Fig. 6) to be taken into account.

The condensation and evaporation in each grid column are determined from the water continuity equation

$$\frac{dq}{dt} = e - c, \quad (5)$$

where t is time, e is evaporation and c is condensation. In terms of partial derivatives, (5) may be written as

$$\frac{\partial q}{\partial t} + \omega \frac{\partial q}{\partial p} + \underline{v} \cdot \nabla q = e - c, \quad (6)$$

where \underline{v} is the horizontal wind. The anvil is assumed to be in a steady state throughout the compositing period. Therefore, (6) becomes

$$\omega \frac{\partial q}{\partial p} + \underline{v} \cdot \nabla q = e - c. \quad (7)$$

To evaluate $e - c$, a specific humidity field was derived for the anvil. Because of difficulties with measuring the humidity in the anvil cloud, the q field in the anvil was obtained at upper levels using observed temperatures and applying relative humidities. At $p = 200$ and 300 mb, ice saturation was assumed, while at 450 mb, the q was set halfway between

the values of ice and water saturation. At levels 650 mb and below, the observed specific humidities were used to represent the unsaturated conditions in the mesoscale downdraft below the anvil. A polynomial fit was used to interpolate between map levels to give vertical continuity of q in each 50 km x 50 km column. An example of a vertical cross section of the q field obtained this way is shown in Fig. 7. This cross section coincides with the vertical motion cross section in Fig. 6.

The composited fields of ω , q and \underline{v} were used to compute $e - c$ according to (7) level-by-level in each vertical column in the anvil region. The field of $e - c$ in the cross-section corresponding to Figs. 6 and 7 is shown in Fig. 8. Integrations of $e - c$ with respect to height and area were carried out as follows,

$$C_{mu} = -\frac{\tau}{g} \iint_{A_a} \int_{P_{TA}}^{P_m} (e - c) dp dA \quad (8)$$

and

$$E_{md} = \frac{\tau}{g} \iint_{A_a} \int_{p_m}^{p_s} (e - c) dp dA \quad (9)$$

where A_a is the area of the anvil region rectangle, P_{TA} refers to the top of the anvil (150 mb), p_s is the surface pressure (1014 mb) and p_m is the pressure of the level where $e - c$ changes sign, i.e. at the anvil cloud base. Specifically, p_m was located at the height within each grid column where $\omega = 0$.

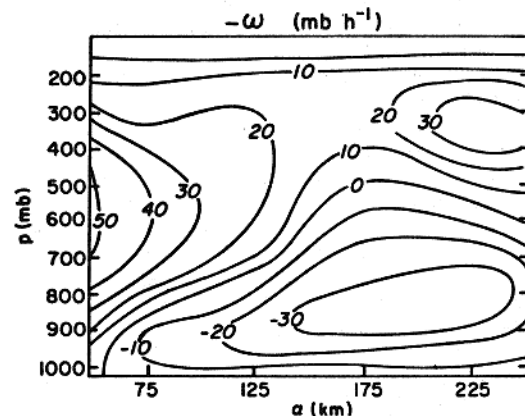


Figure 6. Vertical velocity (ω) cross section extending from front to back through the anvil region.

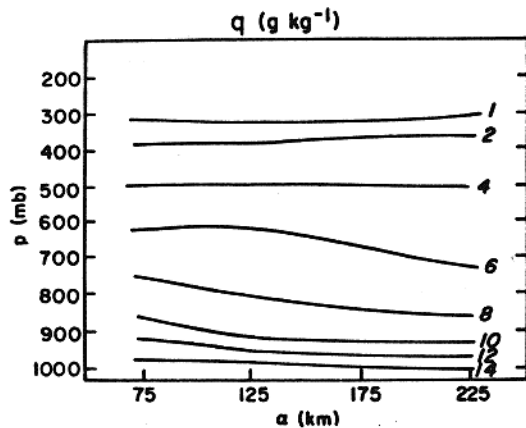


Figure 7. Same as Fig. 6, for specific humidity (q).

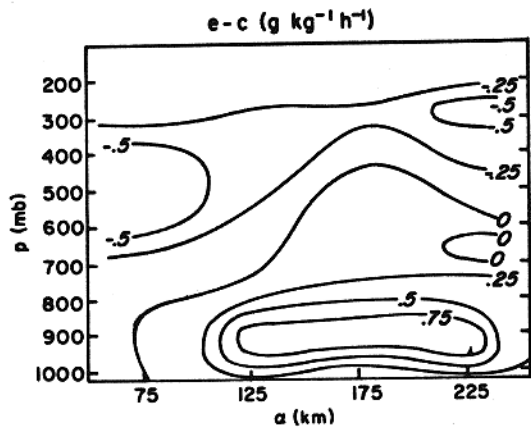


Figure 8. Same as Fig. 6, for evaporation minus condensation ($e-c$).

3.4 Calculation of Evaporation of Condensate in Environmental Air

Evaporation of convective cell condensate into environmental air is assumed to have occurred as air flowed horizontally into the squall-line region from the front, around individual towers and into the anvil region (cf. Sec. 2). It is assumed that environmental air in the mid to upper troposphere entered the front of the squall-line region unsaturated and left saturated, when it crossed the back edge of the squall region and entered the anvil-cloud region. Accordingly, E_{ce} was determined by

$$E_{ce} = \frac{\lambda T}{g} \int_{P_{TA}}^{P_m} V_{ir} [q^*(T_{we}) - q_e] dp, \quad (10)$$

where λ is the length of the front of the squall-line rectangle (150 km), $q^*(T_{we})$ is the saturation specific humidity at the environmental wet-bulb temperature T_{we} , q_e is the actual environmental specific humidity, and V_{ir} is the inward

directed component of the relative wind at the front of the squall-line rectangle.

The evaporation of anvil water into the squall-system environment (E_{me}) was determined from the relative winds observed at the rear of the anvil and an assumption that the anvil cloud water and ice concentration had a value equal to 0.5 g kg^{-1} . Then the amount of water that left the anvil to evaporate in the large-scale environment is given by

$$E_{me} = \frac{1}{g} \int_{P_{TA}}^{P_m} \oint_{\ell_a} q_{cm} \delta \underline{V}_r \cdot d\underline{n}, \quad (11)$$

where ℓ_a is the outer boundary of the anvil region rectangle, \underline{n} is the outward pointing normal vector, \underline{V}_r is the relative wind and δ is unity for outflow and zero for inflow.

3.5 Measurement of Convective Cell and Anvil Rainfall

GATE radar data were used to determine the total amount of rain that fell in the squall-line (R_c) and anvil region (R_m) rectangles during the 9 hour time period of the m composite analysis. The amounts were $R_c = 6.2 \times 10^{11} \text{ kg}$ and $R_m = 7.0 \times 10^{11} \text{ kg}$.

4. RESULTS

Using Eqs. (3) and (4) and (8) - (11) to calculate the condensation and evaporation terms, C_u , E_{cd} , C_{mu} , E_{md} , E_{ce} , and E_{me} , from wind and moisture data and radar measurements to determine the precipitation amounts R_c and R_m , as noted in Sec. 3.5, we obtained values for all the water budget parameters in Eqs. (1) and (2) and Fig. 1 except C_A , which expresses the transfer of condensate from the squall-line to the anvil region. C_A was determined as a residual in both Eqs. (1) and (2) after substitution of the various calculated and measured terms. The results are summarized in Fig. 9 and Table 1.

In Table 1, our results are compared with the three hypothetical water budgets (A, B and C) of LH. Numbers in the table are expressed as fractions of the total system rainfall ($R_c + R_m$). In Leary and Houze's examples R_c and R_m were assumed to be 60% and 40%, respectively, of the total. Hence, they are given as 0.60 and 0.40 in Table 1. In our case, the radar observations showed R_c and R_m to be 47% and 53%, respectively, of the total (Sec. 3.5) and they are therefore given as 0.47 and 0.53 in Table 1. Leary and Houze's assumption of a 60:40 ratio of convective cell to stratiform anvil rain was based on Houze's (1977) case study of a GATE squall line and Cheng and Houze's (1977) statistical study of GATE rainfall. Both studies suggested this ratio was typical. The 47:53 ratio of convective to stratiform rain in our case is not significantly different from these previous studies and indeed further confirms that the rainfall from mesoscale convective systems in the tropics is about half stratiform.

The hypothetical water budgets (A, B and C) of LH were postulated as being three

fundamentally different ways to explain the observed 60:40 ratio of convective to stratiform rain in their mesoscale system.

In Case A, it was assumed that the stratiform anvil rain was produced without any mesoscale updraft or downdraft motion. Hence, C_{mu} and E_{md} were both zero. The only condensation was in the updrafts of convective cells (C_u), and the only way to explain the anvil precipitation was via a large transfer (C_A) of condensate from the cells into the anvil cloud. Thus, C_A nearly matched R_m in Case A.

In Case B, it was assumed that there was no mesoscale updraft in the anvil cloud but that there was a substantial mesoscale downdraft. Thus, again, the convective cells had to provide the condensation for the entire mesoscale system. Moreover, since enough condensate had to be supplied to the anvil not only to explain the observed anvil rain R_m but also to account for the water evaporated in the mesoscale downdraft (E_{md}), the amount of condensation in cells (C_u) and the transfer of condensate from cells to anvil (C_A) had to be greater than in Case A.

In Case C it was assumed that the anvil region of the mesoscale system had both a strong mesoscale downdraft and a well developed mesoscale updraft. In this case some condensation (C_{mu}) occurred in the mesoscale updraft within the anvil region itself. Therefore, the anvil precipitation (R_m) and mesoscale downdraft evaporation (E_{md}) did not have to be supplied entirely by transfer of condensate from cells (C_A). Hence C_u and C_A were smaller in Case C than in Case A. Case C was devised by LH such that mesoscale updraft condensation in the anvil cloud (C_{mu}) and transfer of condensate into the anvil region from cells (C_A) contributed equally as sources of anvil water (Table 1 shows $C_{mu} = C_A$ in Case C). In this respect, Case C resembles Brown's (1979) numerical model simulation of a tropical squall line in which also roughly half (44%) of the anvil water was produced by mesoscale updraft condensation.

Our calculations for the GATE 12 September squall-line system show a water budget that lies between the hypothetical Cases B and C of LH. In the anvil region, both mesoscale updraft condensation (C_{mu}) and mesoscale downdraft evaporation (E_{md}) were substantial, though not quite as strong as in the hypothetical Case C. Our values of C_{mu} and E_{md} are 65% and 72%, as large as those of Case C, respectively. Since our C_{mu} was not as large as in Case C, the amount of condensate that had to be transferred from cells to anvil (C_A) exceeded C_{mu} . The two estimates of C_A , obtained as residuals in Eqs. (1) and (2), are seen in Table 1 to be 0.78 and 0.65, respectively. Thus, C_A exceeded mesoscale updraft condensation C_{mu} (which has a value of 0.26) as a source of anvil condensate by a factor of 2.5 to 3.0. Or, since the total water supplied to the anvil cloud was $C_{mu} + C_A$, C_{mu} accounted for some 30-40% of the total, while C_A accounted for 60-70%. Clearly, the physical processes represented by C_{mu} and C_A were both important to the water budget of the anvil cloud.

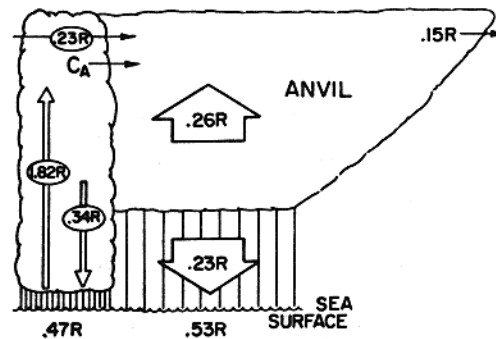


Figure 9. Same as Fig. 1, except all symbols but C_A have been replaced by numerical values determined from data.

Table 1. Water budget of the 12 September 1974 GATE squall-line system compared with the hypothetical water budgets (A, B and C) of Leary and House (1980). Budgets for squall-line and anvil regions are expressed in terms of Eqs. (1) and (2), respectively. Numbers are given as fractions of the total system rainfall ($R_c + R_m$).

Squall-line Region

$$R_c = C_u - E_{cd} - E_{ce} - C_A$$

12 September	0.47 = 1.82 - 0.34 - 0.23 - 0.78
A	0.60 = 1.30 - 0.17 - 0.09 - 0.44
B	0.60 = 1.75 - 0.23 - 0.12 - 0.80
C	0.60 = 1.25 - 0.16 - 0.09 - 0.40

Anvil Region

$$R_m = C_{mu} - E_{md} - E_{me} + C_A$$

12 September	0.53 = 0.26 - 0.23 - 0.15 + 0.65
A	0.40 = 0 - 0 - 0.04 + 0.44
B	0.40 = 0 - 0.32 - 0.08 + 0.80
C	0.40 = 0.40 - 0.32 - 0.08 + 0.40

5. CONCLUSIONS

A water budget of a tropical squall-line system has been derived from GATE radar data and GATE upper-air soundings and surface data composited with respect to the radar observations. The results confirm that about half the precipitation from such a disturbance is stratiform and falls from a deep anvil cloud. A mesoscale updraft occurred in the anvil cloud and a mesoscale downdraft occurred below the anvil. Condensation in the mesoscale updraft accounted for 30-40% of the water in the anvil cloud, while transfer of condensate from convective cells into the anvil region accounted for the remaining 60-70%. From these results, the anvil cloud of a tropical mesoscale convective system appears to be an entity partly maintained by its own vertical air motions but also largely dependent on moisture from neighboring convective cells.

6. ACKNOWLEDGMENTS

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