THE GATE SQUALL LINE OF 9—10 AUGUST 1974

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ABSTRACT

A tropical squall line that passed over the ship array of the Global Atmospheric Research Programme's Atlantic Tropical Experiment (GATE) on 9—10 August 1974 is analyzed. This squall line was similar to squall systems that passed over the GATE ship array on four other days. It began as a purely convective cloud line, then developed an associated stratiform cloud and precipitation area. The stratiform rain built up to a maximum amount over a period of 8 h, then gradually diminished over a 6 h period. This stratiform rain is estimated to have accounted for 32% of the squall system's total precipitation. As in other GATE squall lines, the upper-level cloud shield from which the stratiform rain fell, was advected slowly forward of the line during the system's lifetime, the leading line of convective clouds consisted of transient smaller-scale convective elements, which lent the line an irregular shape and pulsatory movement, and the stratiform portion of the system was characterized by the development of a mid-level mesoscale vortex similar to that seen in other GATE cases.

I. INTRODUCTION

During the Global Atmospheric Research Programme's Atlantic Tropical Experiment (GATE), five westward propagating squall lines passed over the primary observing network, which consisted of an array of ships centered over the eastern tropical Atlantic at 8.5° N, 23.5° W. These squall lines were distinct from most other lines of convective clouds in this region by virtue of their rapid movement (7—14 m/s). They all appeared to be disturbances of the type identified by Hamilton and Archbold (1945) and Zipser (1969); a curved leading band of convective clouds was followed by a mesoscale region of stratiform cloud and precipitation. The passages of these squall lines over the ship array occurred on 28 June, 9—10 August, and 4—5, 11 and 12 September. Of these cases, only the 9—10 August case has not been discussed previously in the literature (Table 1). We have examined this case by subjecting it to an analysis similar to that performed by Houze (1977) on the 4—5 September case. The purpose of this article is to describe the results of this analysis and compare the 9—10 August disturbance with other GATE squall lines.

Table 1. Squall Lines That Passed over the GATE Ship Array

Dates of Passage	References
28 June 1974	Houze and Reppaport (1984)
9—10 August 1974	Wei and Houze (this paper)

4—5 September 1974	Houze (1977)
11 September 1974	Leary and Houze (1979) Gamache and Houze (1985)
12 September 1974	Gamache and Houze (1982, 1983, 1985), Leary and Houze (1979)

II. DATA

The radar data used in this study were microfilms of scope displays and 4 km resolution hard-copy maps of radar reflectivity derived from the digitally recorded data of the radars aboard the ships *Oceanographer* and *Quadra.* The satellite data were in the form of 23 km resolution maps of blackbody temperature measured by the geosynchronous satellite SMS-1. The upper-level wind data referred to were from the final validated GATE ship soundings. The radar and wind data are available through the GATE data catalog (available from the National Climatic Center, Asheville, NC 28801, USA). The satellite data maps [also used by Houze and Rappaport (1984)] were derived from the gridded infrared satellite data archived at the National Center for Atmospheric Research by Smith *et al.* (1979).

III. TRACK AND STRUCTURE OF THE CONVECTIVE LINE

The successive positions of the leading edge of the convective precipitation region of the 9—10 August squall line are shown in Fig. 1. As in the other squall systems that passed over the GATE ship array (see references given in Table 1), the primary component of motion was westward. The line began by moving southwestward at about 9.5 m/s, then turned to a more

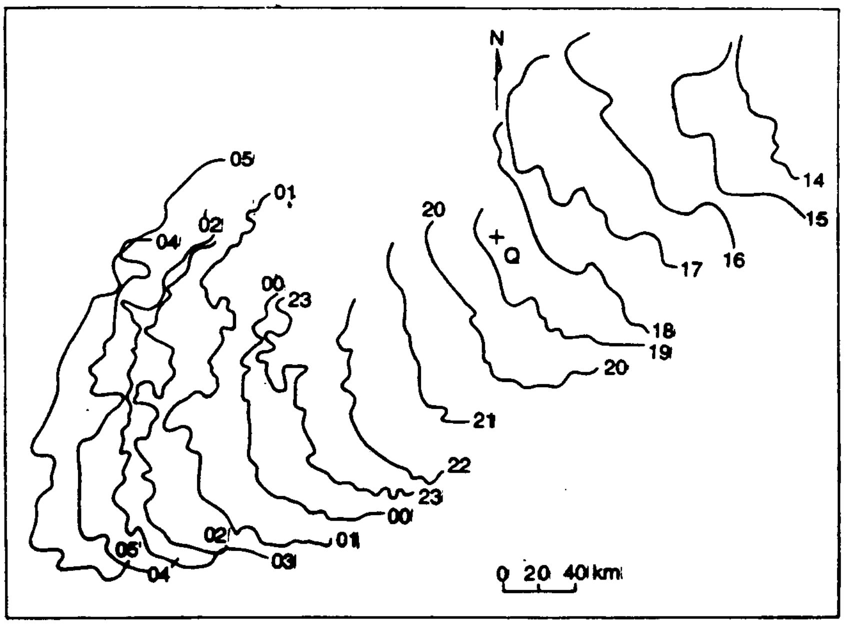

Fig. 1. Isochrones of leading edge of convective radar-echo zone of the GATE squall line. Times are to the nearest hour (GMT). Data from 1408—1800 GMT are from radar aboard the ship *Quadra* (Q). Data from 1900—0500 GMT are from the *Oceanographer* (0).

nearly westward track and slowed to 5—8 m/s late in its life. These speeds are within the range of those observed in the other cases listed in Table 1. The more rapid early southwestward propagation turning to a slower, more westward motion later in the life of the 9—10 August squall line was especially similar to the behavior of the 4—5 September case [compare Fig. 1 with Fig. 1b of Houze (1977)]. Another feature similar to the 4—5 September case was the growth of the length of the convective line during the latter half of its lifetime. After about 2300 GMT on 9 August, the northern and southern extensions of the line became evident. They moved more slowly than the central portion of the line. Thus, the line developed into a more pronounced arc-like or parabolic shape as it lengthened. The northern and southern extensions of the squall line during the second half of the system's lifetime probably were the result of convective clouds forming at the edge of the boundary of low-level downdraft outflow behind the line (Houze, 1977; Zipser, 1977; Fitzjarrald and Garstang, 1981a, b; Johnson and Nicholls, 1983).

The detailed shape of the leading edge of the 9—10 August squall line can be seen from Fig. 1 to have been quite variable in both space and time. This behavior was typical of GATE squall lines. These lines did not display uniformity in the along-line direction. Rather they consisted of a sequence of relatively short-lived convective elements distributed along the length of the line. Houze (1977) identified and tracked 21 "line elements (LE's)" in the radar reflectivity data of the 4—5 September case. These precipitation elements had average lengths of 60 km and widths of 25 km at their times of maximum size, and their average lifetime was 2.4 h. GATE aircraft data show that the actual updrafts and downdrafts in convective regions such as LE's were concentrated on a still smaller scale, the typical draft widths being 1 —2 km (LeMone and Zipser, 1980; Zipser and LeMone, 1980).

In the 9—10 August squall line, 20 line elements were identified in the radar reflectivity data and tracked. Their average lifetime was 2.6 h, a value similar to that found in the 4—5 September case (Houze, 1977). Their typical horizonal dimension at time of maximum size was 15 km. (Although this horizontal dimension is less than those found for the LE's on 4—5 September, it may not indicate a real difference in size since the value of the reflectivity contour chosen for tracking probably influenced the size of the feature identified.)

The maximum echo heights of the LE's on 9—10 August ranged 9—13 km, considerably less than the average 16 km maximum heights on 4—5 September, but similar to the maximum heights of 8—16 km (typically 12 km) as seen on 28, June. The heights in the case of 9—10 August might appear to have been greater than the 4—11 km heights seen on 12 September. However, the heights in the 12 September case were probably not actually much different from those seen on 9—10 August since the heights in the 12 September case were determined from the radar on the ship *Researcher,* while those in the 9—10 August case (as well as those on 28 June and 4 September) were determined from the *Oceanographer* radar, which was more sensitive to weak echo and, therefore, prone to detect cells to greater heights.

IV. MESOSCALE PRECIPITATION PATTERN AND UPPER LEVEL CLOUD SHIELD

In Fig. 2, radar reflectivity patterns and infrared satellite imagery have been overlaid for two times. The data for 2000 GMT represent the earlier period of the 9—10 August squall-line, while the data for 0100 GMT represent its later period. The radar data indicate the low-level rainfall pattern at each time, while the satellite contour outlines the boundary of the coldest portion of the upper-level cloud shield (defined here by a threshold equivalent blackbody temperature of -47°C).

At each time, the rainfall pattern can be seen to have consisted of a band of more intense (convective) rain followed by a broad region of less intense (stratiform) precipitation. By the later time, the convective band had broken up into a discontinuous series of intense radar–echo regions, while the trailing stratiform region had become larger. This precipitation structure is similar to that of the other squall lines listed in Table 1; each of them was characterized by a leading band of convective rain followed by a well defined mesoscale region of stratiform precipitation. In vertical cross sections, the stratiform precipitation in the 9—10 August case exhibited a distinct melting layer on radar very similar to those shown for the cases of 28 June, 4—5 September, 11 September and 12 September by Houze (1977), Leary and Houze (1979) and Houze and Rappaport (1984).

The region of upper-level cold cloud-top on 9—10 august was approximately centered over the radar–echo area at 2000 GMT (Fig. 2a). By 0100 GMT, however, the cold cloud top had moved forward so that it extended well ahead of the leading edge of the low-level convective rainband (Fig. 2b). This movement of the high cloud ahead of the squall line was in accordance with the 200 hPa level winds (to be discussed below) and consistent with the behavior of the cloud shields observed in the squall lines of 28 June, 4—5 September and 12 September. On 12 September [Fig. 4 of Gamache and Houze (1983)] and 4—5 September [Fig. 15 of Houze (1977)], the high cloud tended to trail the band of intense convective rainfall. On 4—5 September, the cold cloud moved gradually forward from a position entirely behind the line in the system's earlier stages to a position centered directly over the convective line during its later stages. In the case of 8 June [Fig. 2 of Houze and Rappaport (1984)], the area of cold cloud top was centered over the convective line in its early period, but by the time the system reached maturity the cold cloud had extended forward of the convective line and was actually depositing stratiform rain ahead of the convective line. Thus, the GATE squall systems consistently exhibited forward movement of the region of cold cloud top, although the distance ahead of the line reached by the leading edge of cold cloud varied considerably from case to case.

V. WIND OBSERVATIONS

Relative winds and streamlines in the vicinity of the 9—10 August squall-line are shown

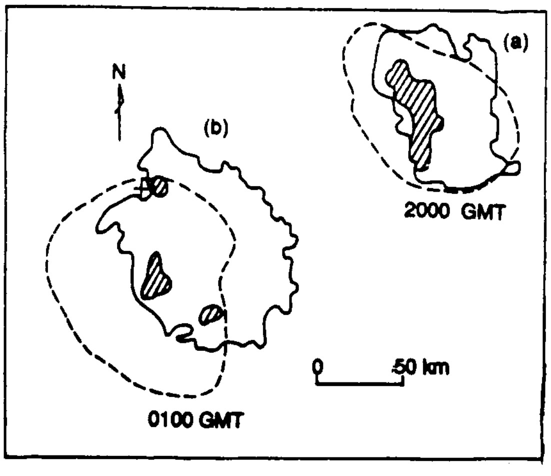

Fig. 2. Cloud and precipitation pattern associated with the 9—10 August 1974 GATE squall line at two times. Dashed line outlines satellite infrared isotherm for −47°C (11 km) level. Solid line encloses low-altitude precipitation detected by radar on board the *Oceanographer* (located at the cross). Shaded areas contain higher intensity radar echoes.

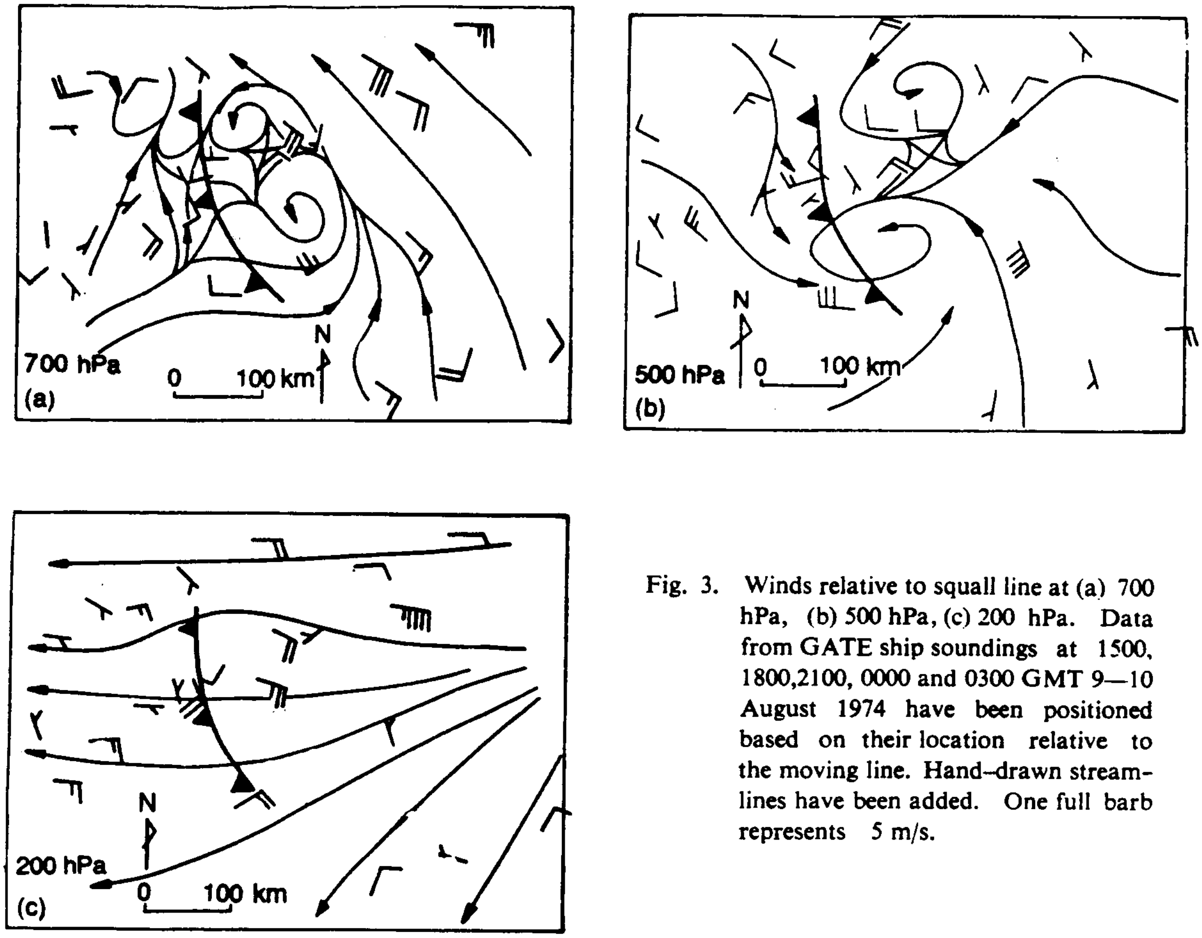

Fig. 3. Winds relative to squall line at (a) 700 hPa, (b) 500 hPa, (c) 200 hPa. Data from GATE ship soundings at 1500, 1800,2100, 0000 and 0300 GMT 9—10 August 1974 have been positioned based on their location relative to the moving line. Hand–drawn streamlines have been added. One full barb represents 5 m/s.

for three levels in Fig. 3. The maps contain data obtained at GATE ships during the period 1500 GMT 9 August through 0300 GMT 10 August. The relative winds were obtained by subtracting the average squall-line velocity during this period (from 65° at 8.5 m/s) from the observed winds. The boundary shown represents the average length and shape of the squall line during this period. The wind observations were located relative to this line on the basis of the ships' positions in relation to the actual squall line at each observation time.

The individual wind reports are somewhat erratic as a result of well known instrumental noise in the GATE soundings (Reeves, 1978) and because winds from different times have been combined to form composite patterns. The data nonetheless indicate the smoothed flow depicted by the streamlines, and this flow generally confirms mesoscale flow features seen in the other GATE squall lines. Most significant is the tendency of the mid-tropospheric flow to break down into mesocyclonic vortices to the rear of the squall line (in the vicinity of the stratiform precipitation region). A double vortex structure is seen at both the 700 and 500 hPa levels to the rear of the 9—10 August squall-line (Fig 3a and b). A weaker cyclonic signal was seen at 850 hPa (not shown). Midtropospheric mesoscale cyclonic vortices were also seen to the rear of the squall lines of 4—5 September, 12 September and 28 June (Fig. 5c of Houze, 1977; Fig. 7b of Gamache and Houze, 1982; Fig. 4 of Gamache and Houze, 1985; and Figs. 14 c and 16 of Houze and Rappaport, 1984). The flow at 500 hPa on 9—10 August (Fig. 3b) shows a strongly convergent pattern, characterized by relative inflow from all directions. In the case of 12 September, Gamache and Houze (1985) also found the strongest mesoscale convergence pattern at about the 500 hPa level.

The higher-level flow at 200 hPa (Fig. 3(c)) confirms the diffluent flow aloft seen above the other GATE squall lines (cf. Fig. 5(c) of Houze, 1977; Fig. 10(a) of Gamache and Houze, 1982; Fig. 18 of Houze and Rappaport, 1984), and its strong component directed across the squall line from the rear toward the front of the system is consistent with the forward relative motion exhibited by the upper-level cloud shield described in Section IV and rather similar to the 28 June case (Fig. 18 of Houze and Rappaport, 1984).

VI. CONVECTIVE AND STRATIFORM RAIN AMOUNTS

The radars aboard the GATE ships *Quadra* and *Oceanographer* showed the detailed precipitation pattern of the squall system throughout its history. From the data of these radars, time series of the rainfall in the convective and stratiform regions have been constructed (Fig. 4). To obtain these curves, the boundary between the convective and stratiform regions was identified subjectively following guidelines similar to those discussed and used by Houze (1977), Gamache and Houze (1983) and Houze and Rappaport (1984). Often a minimum of reflectivity existed between the convective and stratiform regions, and it was used to help establish this boundary. We corrected radar reflectivity values for instrumental bias and attenuation by atmospheric gases according to Hudlow et al. (1979), and we used their Z-R relationship ($Z=230R^{1.25}$, where Z is the equivalent radar reflectivity factor in $\mathrm{mm}^6/\mathrm{m}^3$ and R is rainfall rate in mm/h) to obtain rainfall rate from the corrected reflectivity.

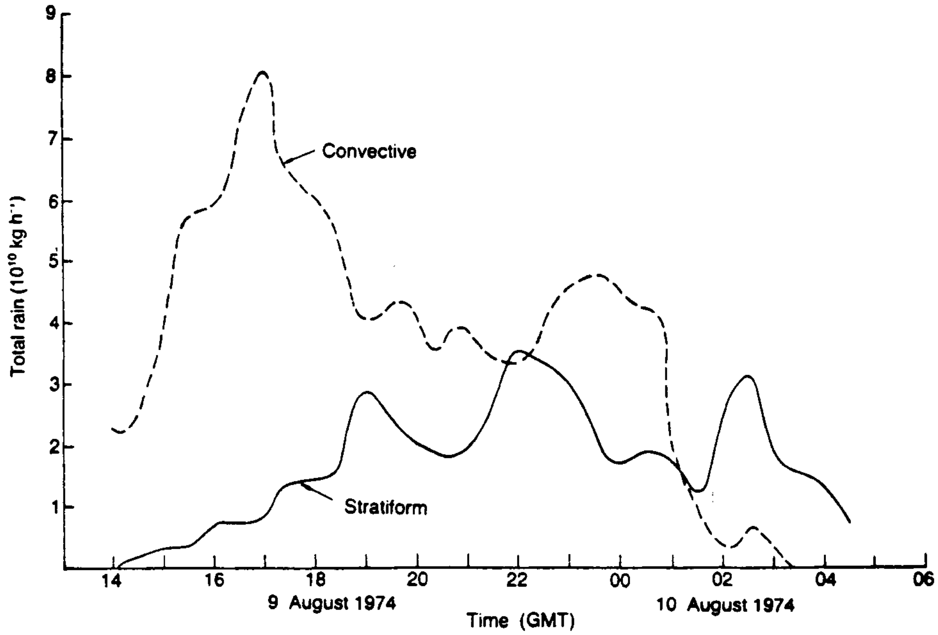

Fig. 4. Time variation of total rain integrated over areas covered by the convective and stratiform regions of the 9—10 August 1974 GATE squall system.

The curves in Fig. 4 are from the *Oceanographer* radar data after 1900 GMT on 9 August and from the *Quadra* radar for the period before 1900 GMT. Between 1900 and 2330, data from both radars were available. During this period of overlap, the area-integrated rain rates from *Quadra* were found to be systematically larger than those from *Oceanographer*. The source of this discrepancy is not known. To obtain consistent curves we arbitrarily reduced values from the *Quadra* according to the ratio $\bar{O}/\bar{Q}$, where $\bar{O}$ and $\bar{Q}$ are the average integrated rain rates at *Oceanographer* ($\bar{O}$) and *Quadra* ($\bar{Q}$) between 1900 and 2330. This ratio was found to be approximately 2 and was applied to both the stratiform and convective regions to obtain the curves shown for the period before 1900 GMT in Fig. 4. Normalizing the data to *Oceanographer* rather than *Quadra* allows more ready comparisons with the rainfall amounts deduced for cases of 28 June, 4—5 September and 12 September, all of which were based heavily on the *Oceanographer* radar. However, since our concern here is primarily with comparing stratiform and convective regions in a relative sense, the normalization used to establish the rainfall-rate scale is of secondary importance.

The curves in Fig. 4 show that the squall system of 9—10 August began as an entirely convective feature. The convective rain reached a maximum amount about 3 h into the system's lifetime. Thereafter, the convective rain progressively decreased. The stratiform rain developed slowly but steadily, as the upper-level stratiform cloud deck developed as an outgrowth of the convective clouds. The stratiform precipitation amount reached a maximum at about 8—9 h into the system's lifetime. In the cases of 4—5 September (Fig. 26 of Houze, 1977) and 28 June (Fig. 8b of Houze and Rappaport, 1984), the stratiform rain amount reached a maximum at 10 h after system initiation. The stratiform precipitation amount on 9—10 August took about 6 h to decline after its peak was reached (compared to a 14 h decline in the case of 4—5 September and 8 h in the case 28 June). As on both 28 June and 4—5 September, the convective rain amount on 9—10 August decreased in parallel with the stratiform amount. In all three cases, the convective and stratiform rain died out nearly simultaneously (within 1—2 h of each other).

The total convective and stratiform rain amounts in the 9—10 August case can be obtained by integrating the curves in Fig. 4 with respect to time. The stratiform rain is found to account for 32% of the rain from the entire squall system. The fraction is somewhat less than the 40% found in the 4—5 September case (Houze, 1977), 49% on 12 September (Gamache and Houze, 1983) and 42% on 28 June (Houze and Rappaport, 1984). These 4 cases suggest that in general 30—50% of the precipitation of a tropical oceanic squall line is stratiform. These figures are also similar to the 30—40% stratiform rain found by Leary (1984) and 46% found by Churchill and Houze (1984) for non-squall cloud clusters over tropical oceans.

VII. CONCLUSIONS

Analysis of the 9—10 August 1974 GATE squall line confirms aspects of structure seen in four other tropical squall lines sampled by the GATE ship array. The line exhibited early rapid movement followed by gradual turning and slowing. The movement of the line was irregular and pulsatory, as a result of its containing discrete transient convective elements. A trailing region of stratiform precipitation developed progressively as an outgrowth of the convective line and eventually accounted for about 32% of the rain that fell from the squall system. A mid-level mesoscale vortex formed in the stratiform region. The stratiform rain area began to weaken immediately after reaching its maximum size, and it died out at about the same rate as the convective region. The upper-level cloud shield marking the top of the squall system was advected forward of the low-level squall line by winds aloft.

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