

GATE RADAR OBSERVATIONS OF A TROPICAL SQUALL LINE

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1. INTRODUCTION

In middle latitudes, one of the most formidable convective phenomena is the squall line (Newton, 1963). Squall lines are also significant weather systems in the tropics. A descriptive account of West African squall lines was first given in the early synoptic study of Hamilton and Archbold (1945). More recent descriptions of tropical squall lines have been given by Zipser (1969) and Betts *et al.* (1976). A tropical squall line basically consists of a row of cumulonimbus clouds continually being regenerated by low-level convergence at the edge of a broad downdraft region located below a trailing anvil cloud (Fig. 1).

This paper describes observations obtained on 4 September 1974 when an excellent example of a tropical squall line moved over the C-band radar-equipped NOAA ship *Oceanographer* (see front cover), which was located at 7.8°N 22.2°W for GATE (the Global Atmospheric Research Program Atlantic Tropical Experiment). These GATE radar observations show the squall line's structure in much more detail than has been possible in previous studies of tropical squall lines.

2. SYNOPTIC SITUATION

The 700 mb map for 1200 GMT on 4 September 1974 showed a pronounced synoptic-scale wave in the tropical easterlies, with a trough 700 km to the east of the GATE area and a ridge 500 km to the west. The squall line observed on radar moved faster than the large-scale wave, propagating southwestward from the trough region toward the ridge. The squall line stalled and dissipated before actually reaching the ridge.

3. HORIZONTAL STRUCTURE AND MOTION

Quantitative PPI displays from the *Oceanographer* radar (wavelength 5.30 cm, beam-width 1.5°, peak power 215 kW*) are shown in Fig. 2. Time-lapse movies of the PPI displays at 5 min intervals show three distinct echo regions: a region ahead of the squall line, the squall line itself (indicated by arrows in Fig. 2) and a region trailing the squall line.

*For more detailed descriptions of the *Oceanographer* shipboard radar system, see Hudlow (1975a and b).

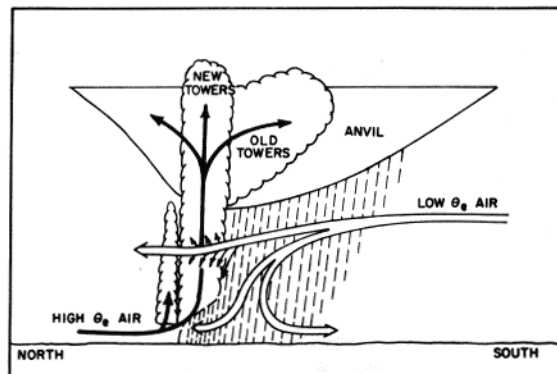


Fig. 1. Air flow relative to a squall line system according to Zipser (1969). Θ_e is equivalent potential temperature.

In the region ahead of the squall line, the radar echoes were at first concentrated in a long line perpendicular to the approaching squall line (Figs. 2a-d). This line gradually dissipated, however, and the echo pattern ahead of the squall line became rather chaotic (Figs. 2f-h). Neither individual echo cores nor the larger aggregates of echoes showed much movement in the region ahead of the squall line. Instead, the echoes tended to grow and dissipate almost in place.

In sharp contrast, the squall line moved rapidly toward the southwest at 12 m s⁻¹ (Figs. 2a-j). Careful examination of radar echoes during GATE shows that such rapid echo motion was associated only with squall lines (Houze, 1975).

The region behind the squall line was characterized by an extensive zone of relatively light stratiform precipitation. This light rain was best seen after the squall line had passed over the ship (Figs. 2i-j). Before that time (Figs. 2a-h), echoes from the light rain behind the squall line were seen only in patches. Echoes from the light rain were apparently weakened as a result of attenuation when the intense squall line was located between the radar and the stratiform zone. The location of a broad zone of light rain immediately behind the squall line fits Zipser's model (Fig. 1). According to the model, evaporation occurs in this region as the light rain falls into unsaturated midtropospheric air below the anvil cloud. The resulting cooling drives the extensive downdraft which in turn

spreads out at low levels and triggers convective updrafts in the squall line at its leading edge.

Although the stratiform rain in the region behind the squall line is light in comparison with the heavy rain within the squall line (Fig. 2), the area-integrated rainfall (in $g\ s^{-1}$) for the stratiform anvil region was about one-third of the total for the entire squall line-anvil system. (The tentative relationship, $Z = 350R^{1.25}$, relating reflectivity Z in dbz to rainfall rate R in $mm\ h^{-1}$, suggested by Hudlow (1975a), was used in making this calculation.) Such a large proportion of rain falling in the stratiform region behind the squall line suggests that this precipitation was not simply fallout from inactive debris blown off the tops of cumulonimbus clouds located in the squall line itself. Recent numerical experiments by Brown (1974) suggest that active mesoscale lifting and generation of new precipitation may take place within the anvil cloud, above the evaporatively-driven downdraft zone. Another process which may contribute to the substantial rainfall rates behind the squall line is suggested below in § 4.

4. SQUALL LINE ELEMENTS

The building blocks of the squall line seen in Fig. 2 were small two-dimensional line elements (LE's). By following the six LE's (numbered 1-6 in Figs. 2a-b), it can be seen that the motion of the squall line was a combination of translation and redevelopment, as new LE's systematically formed ahead of the existing squall line while old LE's dissipated at the rear of the squall line. Remnants of the old LE's blended into the region of stratiform rain behind the squall line. The behavior of the LE's was similar to the cells in multicell hailstorms which begin as discrete clouds ahead of the storm and dissipate to the rear (Dennis *et al.*, 1970; Browning *et al.*, 1976).

At 0945 GMT (Fig. 2a), LE 1 was dissipating at the rear of the squall line, LE 2 was at a peak state of development in the center of the line, while LE's 3, 4 and 5 were just beginning to form ahead of the line. LE 5 eventually extended east-southeastward from the point indicated in Fig. 2a. By 1045 GMT (Fig. 2d), LE 2 was weakening at the rear of the squall line, while LE's 3 and 4 were at peak development, each exhibiting a very two-dimensional structure. LE 5 was still in a formative stage ahead of the squall line at this time. By 1145 GMT (Fig. 2f), LE 5 was taking shape rapidly, while LE 3 was dissipating and merging with the trailing stratiform rain. LE 5 was best developed at 1245 GMT (Fig. 2h).

Eleven LE's appeared and disappeared while the squall line was in the area covered by the Oceanographer radar, and each had a life history similar to LE's 1-6. The lifetimes of these LE's were from 1-5 h. They were each 10-40 km in width and 40-170 km in length.

The dissipation of LE's at the rear of the squall line and their subsequent tendency to blend into the stratiform rain behind the squall line suggests that the large rainfall

rates in the stratiform region may be due in part to the sudden cessation of the updrafts producing the LE's which then leaves large quantities of liquid water at all levels aloft. As this water falls, much higher rainfall rates could be observed than if the stratiform rain was from upper-level blowoff alone.

Kessler's (1969) kinematic cloud models show that the sudden cessation of a strong updraft is followed by a rapid rise in cloud base due to collection of all the cloud droplets at low levels by the larger precipitation particles. A dissipated LE could therefore develop a middle- or upper-level cloud base, rendering it indistinguishable from the rest of the anvil structure behind the squall line. The "old towers" in Zipser's model (Fig. 1) might have been recently dissipated LE's.

5. VERTICAL STRUCTURE

a. Construction of RHI's

The Oceanographer radar was operated in a three-dimensional conical scan sequence once every 15 min. This sequence consisted of complete azimuthal sweeps at elevation angles ranging from 0-22°, in increments of approximately 2°. A sequence took 5 min to complete and the data obtained were recorded digitally on magnetic tape in range bins of 2 km and azimuth bins of 2° (Hudlow, 1975a and b).

A computer program was developed by Leary and Houze (1976) to construct and print out RHI displays from the digital tapes. For this study, over 1300 RHI's were printed out to investigate the three-dimensional structure of echoes associated with the squall line. Some highlights of the findings are presented below.

b. Vertical Structure of Echoes Ahead of the Squall Line

A vertical cross section through the echo region ahead of the squall line is shown in Fig. 3. The echoes in this region were characterized by vertically-oriented echo cores.

c. Vertical Structure of a Squall Line Element

The squall line element LE 5 reached its maximum intensity at about 1245 GMT, just as it approached the Oceanographer (Fig. 2h). A vertical cross section through LE 5 is shown in Fig. 4. The sloping structure of the echo in Fig. 4 was typical of all LE's, and contrasts sharply with the vertical echo cores seen ahead of the squall line (Fig. 3). RHI patterns constructed for other azimuths through LE 5 showed a sloping structure similar to that seen in Fig. 4, indicating that LE 5 was essentially two-dimensional. The sloping structure of the LE suggests that it was produced by a sloping updraft.

The updraft apparently originated at low levels just ahead of the LE. The leading edge of the downdraft air, accompanied by a sudden windshift and dry and wet bulb temperature drops (Fig. 5), passed over the Oceanographer just prior to the onset of precipitation from

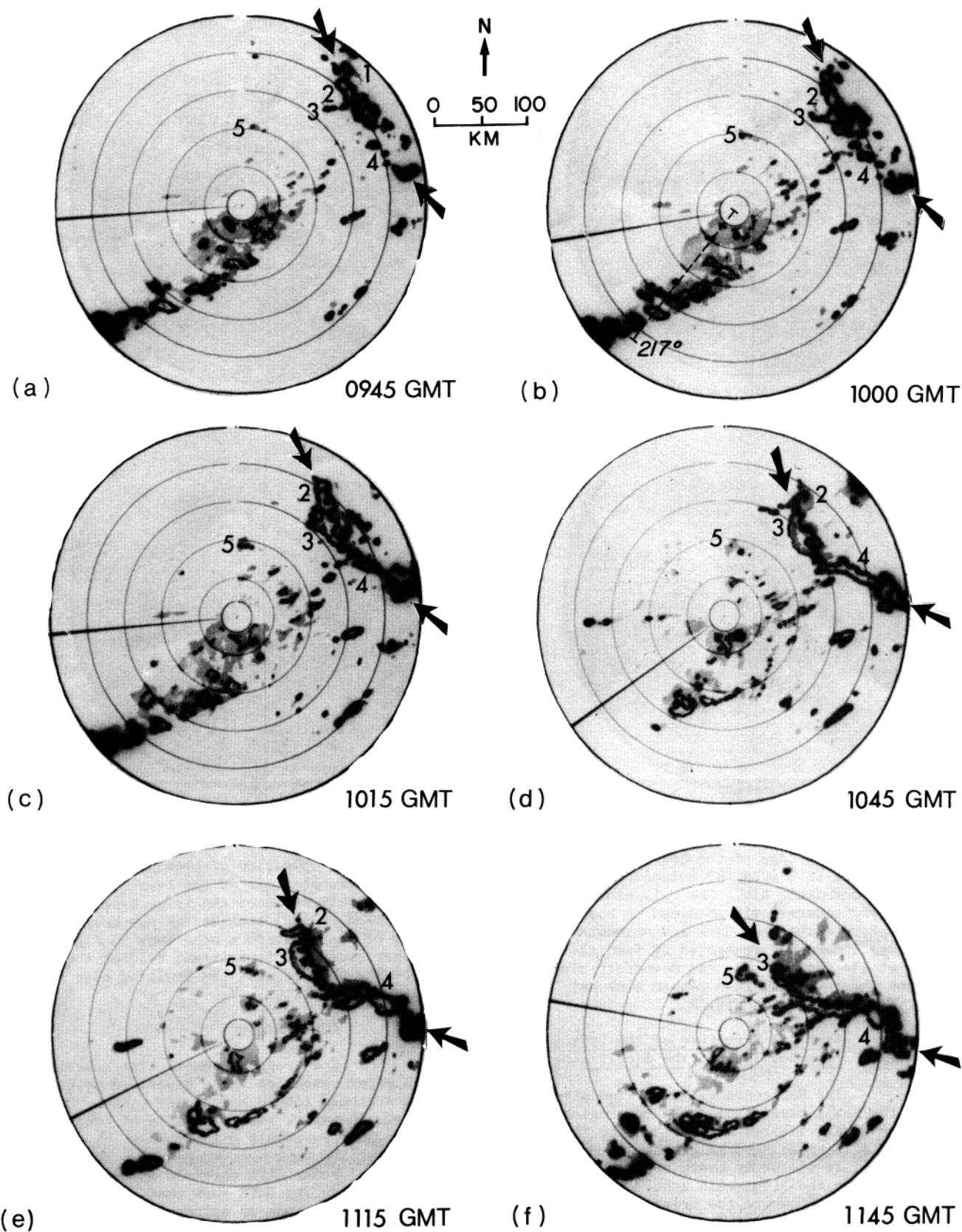


Fig. 2. PPI displays of *Oceanographer* radar, 4 September 1974. Shading thresholds are for minimum detectable signal (gray), 28 dbz (black), 36 dbz (white), and 44 dbz (gray). Radial line indicates ship heading (a 20° sector was blocked by the ship's superstructure in this direction). Arrows indicate squall line. Numbers refer to features mentioned in text. Azimuth lines (dashed) for vertical cross sections shown in Figs. 3, 4, and 6 are labelled in degrees in (b), (h) and (i).

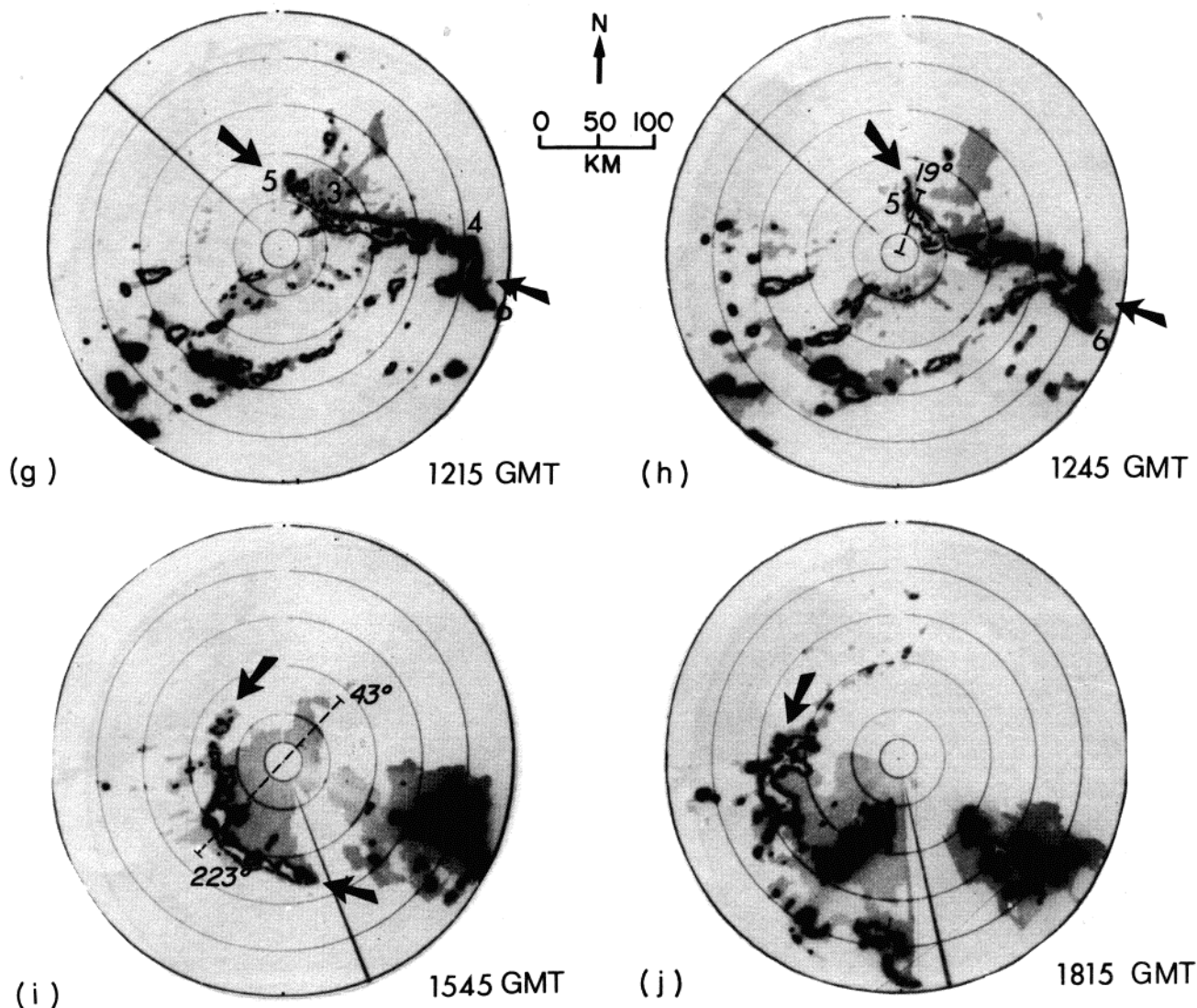


Fig. 2. Continued from previous page.

LE 5. The leading edge of the low-level roll cloud preceding LE 5 (Fig. 4) coincided with the edge of the downdraft air. The roll cloud, seen in an all-sky camera movie obtained on board the *Oceanographer*, was a very dark and ominous-looking feature apparently generated by frontal-like lifting at the edge of the cold downdraft air spreading under the LE, in a manner somewhat similar to that shown in Fig. 1.

d. Vertical Structure of the Stratiform Rain Behind the Squall Line

The horizontally stratified structure of the anvil precipitation in the region behind the squall line is made evident by the appearance of a pronounced bright band near the melting level in virtually every cross section constructed for the light rain zone. An example is shown in Fig. 6, where the bright band (near the 4-km level in the vicinity of the ship) exhibited a slight downward slope. Interpreted as an isotherm, the band slopes in the expected sense, being slightly higher toward the squall line and slightly lower toward the rear (northeast side) of the system where the maximum evaporative cooling would be taking place (Fig. 1).

Evaporation of precipitation falling into the unsaturated air at the rear of the storm system evidently produced the large overhang of precipitation (virga) seen at the northeast boundary of the stratiform echo zone in Fig. 6. From other cross sections it was evident that this large overhang surrounded the trailing edge of the entire stratiform zone.

6. CONCLUSIONS

The tropical squall line described in this paper resembles those described by Hamilton and Archbold (1945) and Zipser (1969). GATE radar data, however, reveal details of squall line structure not previously evident.

Radar data obtained aboard the *Oceanographer* during GATE show that the squall line in this study was an aggregate of small two-dimensional line elements (LE's), 20 km x 100 km in typical dimension. The systematic development of LE's ahead of the existing squall line and dissipation of old LE's at the rear of the squall line contributed to the rapid southwestward movement of the squall line, and lent a stepwise appearance to its motion reminiscent of multicell

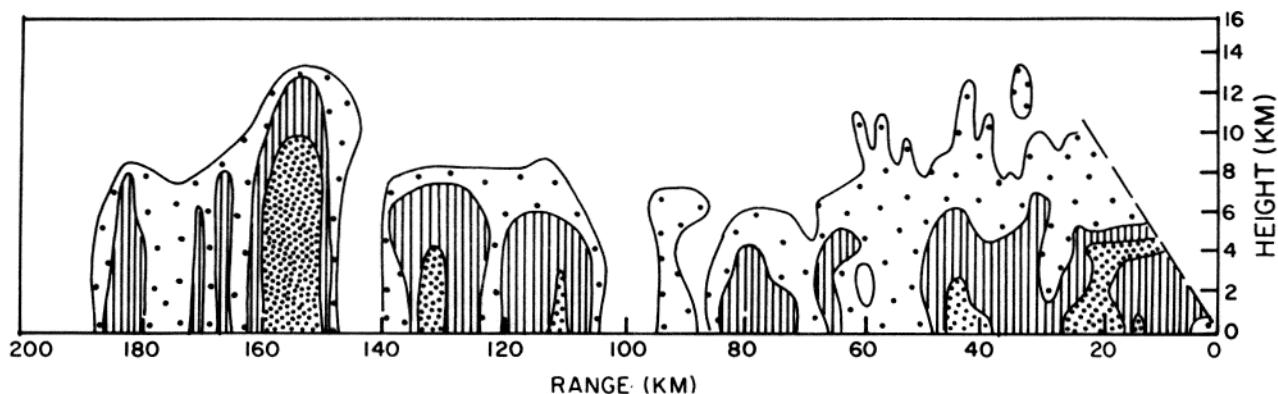


Fig. 3. RHI ahead of squall line, along azimuth 217° , derived from *Oceanographer* radar conical scan sequence for 1000 GMT 4 September 1974. Inside contours are for 20 and 30 dbz. Outside contour is boundary of minimum detectable echo. Dashed line shows maximum beam elevation.

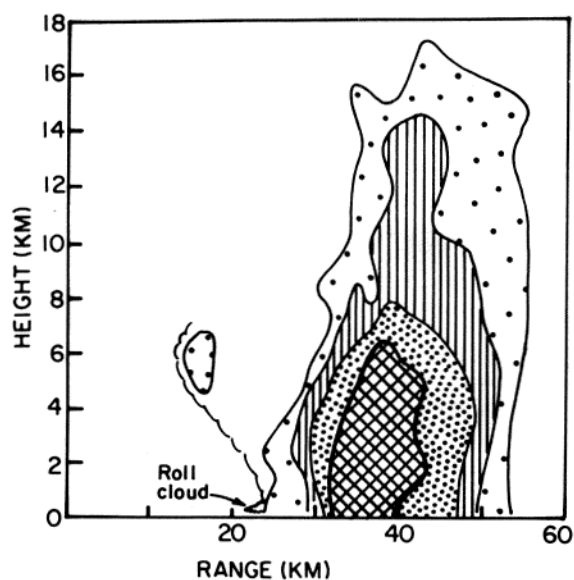


Fig. 4. RHI through a squall line element, along azimuth 19° , for 1245 GMT 4 September 1974. Inside contours are for 20, 30 and 40 dbz. Outside contour outlines weakest detectable echo. Scalloped cloud boundary estimated from all-sky camera data.

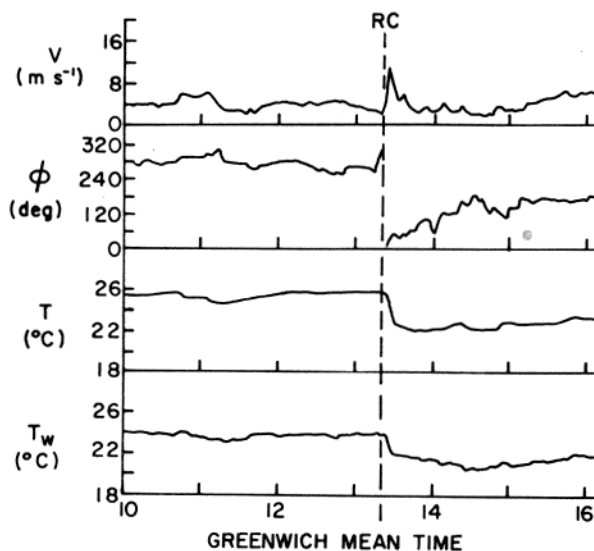


Fig. 5. Surface wind speed (V) and direction (ϕ) and dry (T) and wet (T_w) bulb temperature at *Oceanographer* site on 4 September 1974. RC is time that leading edge of roll cloud passed over ship just prior to onset of squall line precipitation.

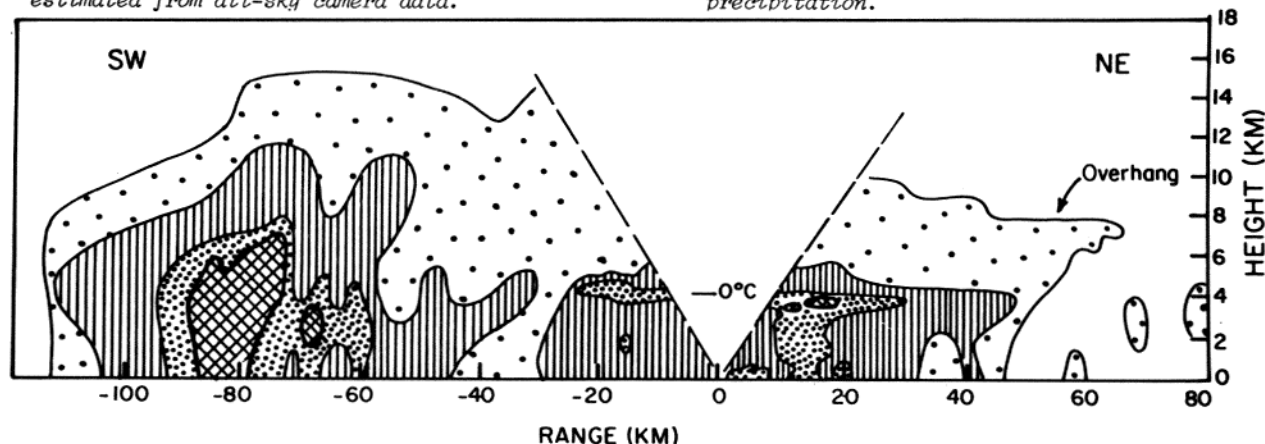


Fig. 6. RHI through entire squall line-anvil system, along azimuths 223° (SW) and 43° (NE) at 1545 GMT 4 September 1974 (see Fig. 2i). Inside contours are for 20, 30, and 35 dbz. Outside contour outlines weakest detectable echo.

hailstorms in mid-latitudes. Vertical cross sections constructed from the three-dimensional digital radar data show that the LE's had a vertically sloping structure which suggests that they were produced by sloping updrafts. As LE's dissipated they merged with the light rain in the anvil region behind the squall line.

The precipitation from the anvil cloud behind the squall line exhibited a highly stratiform appearance in vertical cross sections. Evidence of evaporation below the anvil cloud was seen in the slope of the melting band and by the presence of an overhang structure at the rear of the system. About one-third of the precipitation falling from the squall line-anvil system fell in the stratiform anvil region.

The distinctive structure of tropical squall lines shown by the GATE radar provides a basis for assessing the role of squall lines in the mass and heat budgets of the large-scale tropical atmosphere. The squall line structure is so well-defined in the radar data that it will be possible to determine the amounts of precipitation produced in individual squall line elements as well as in the trailing anvil region and to know approximately the depth of the atmosphere through which updrafts and downdrafts were operating to produce the precipitation patterns. Using appropriate models, the vertical transports of mass and heat accomplished by the air motions producing the observed squall line may then be computed. Convective transports have been computed this way for other convective situations (Austin and Houze, 1973; Houze, 1973; Houze and Leary, 1976), and this approach now promises to be a useful way to study the role of squall lines in the tropical atmosphere.

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