Squall lines observed in GATE

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SUMMARY

A study of convection as portrayed by Oceanographer radar during phase III of GATE reveals four occasions on which an organized line of convection moved with a speed close to or greater than the wind speed at any level. They are shown to resemble closely the analytical model and numerical simulation of tropical line squalls developed by Moncrieff and Miller. This form of organization is associated with a low-level wind maximum in the direction of movement.

I. INTRODUCTION

The cirrus canopy associated with the cloud cluster now familiar from satellite pictures of the tropics has tended to obscure the organization into lines or bands that is revealed by radar data. GATE has provided an opportunity to investigate any such organization and a survey of Oceanographer radar PPIs from 2 to 17 September has shown that some band or line structure is almost always present. These patterns often persist for times large compared with the time taken for air to flow through the system, and so they can be considered for some purposes to represent a quasi-steady state. This tendency towards steadiness and 2-dimensionality allows simplifications to be made in a dynamical description of the flow, as for example, in Moncrieff and Green (1972) and Moncrieff and Miller (1976). It also means that interpretation of soundings in terms of inflow and outflow from the systems is more reliable than if the convection was randomly distributed. Although moving squall lines are frequently observed over the African and South American continents only five of the forty line-systems observed here exhibited substantial movement. This paper compares the structure of these moving lines with the models of Moncrieff and Miller and with similar squall lines observed over land in Venezuela (Betts et al. 1976).

The Oceanographer C band radar has a maximum range of 233 km and a beam width of 1.5°. During phase III of GATE, Oceanographer was positioned in the 'B scale hexagon' at 7°45'N 22°21'W. The data used were photographs of PPI scans at 0.5° elevation every 5 minutes, plus sequences of scans at increasing elevations up to 22° every 15 minutes. Range-compensated echo strengths were indicated by grey shades. Further details of the radar performance and data processing can be found in Hudlow (1975). Hourly PPIs from the Quadra radar were also used to extend the area covered by the investigation and as a support during part of the period when Oceanographer data were of low quality due to pitch stabilization problems. The thermodynamic and wind fields were found from 3-hourly radiosonde ascents from Oceanographer and some surrounding ships. Oceanographer and many other GATE ships used very low frequency (VLF) navigational radio transmissions to track sondes and derive winds. A time section of wind components using Oceanographer's VLF system was compared with radar winds from Hecla and agreement was found in the large-scale features.

2. GENERAL DESCRIPTION

The four squall lines observed at Oceanographer on 4, 11, 12 and 16 September were also visible on Researcher's radar, 160 km to the southwest. Houze (1975) gave a brief
description of these squall lines which is confirmed and expanded here. The systems moved from Oceanographer to Researcher with little change in structure. The first three systems were slightly curved bands with the strongest echoes close to the leading edge and weaker echoes trailing behind. These squall lines were first detected at the northeastern edge of the pictures and moved steadily southwestwards to disappear out of range to the southwest. The squall on the 16th was similar but was not noticeably curved, formed north of the radar, moved south and dissipated within the radar range.

Figure 1. Composite, range-normalized, PPI scan from Quadra and Oceanographer radars (Q and O respectively) for 1100Z 12 September 1974. The darker shading indicates the stronger echoes and corresponds approximately to rainfall in excess of 6 mm/hr. Three different band structures are denoted as follows: a slightly curved rapidly moving squall line (A, indicated by the dotted line); a line of moderate cumulus (B); and a nearly stationary band of deep convection (C).

A fifth moving band of precipitation was visible on the Quadra radar on 12 September. This was the only system clearly visible on satellite pictures, as the cloud tops were low in this case (around 7 km) and no anvil formed to obscure the active convection. Fig. 1 is a composite PPI from Oceanographer and Quadra radars at 1100Z on the 12th. Consideration of a sequence of such pictures shows that the curved band (A) is a separate system from the straight line (B) extending northwestwards. On the satellite pictures for this day anvils spreading out towards the northwest from the stationary band of convection (C) and behind the curved band (A) obscured the organization of these features. The only moving line visible on the satellite pictures was line (B) which moved from 035° at 7·8 m s⁻¹. However, analysis of the radar pictures showed the curved band (A) moving from about 045° at 15·1 m s⁻¹ beneath the cirrus shield. From now on we refer only to the four squall lines visible on Oceanographer radar; the fifth line (B) has been mentioned only to avoid erroneous comparisons with the speed of this line as observed from satellite pictures, and that of the different line (A) viewed by the radar.

On all occasions there was a maximum at about 3–4 km in the wind component in the direction of travel of the lines. There was strong shear in the direction of propagation below the maximum and reverse shear above. The shear changed sign again at about 8 km with a second wind maximum in the same direction at about 12–13 km. The coincidence between
Figure 2. (a) Time–height section of W–E wind component at Oceanographer 2–17 September 1974. Isopleths in m s\(^{-1}\). Regions of easterlies in excess of 10 m s\(^{-1}\) are shown by hatching. The arrows denote the times of arrival of the squall lines. (b) As for (a) but S–N component. Regions of northerly wind in excess of 5 m s\(^{-1}\) are shown by hatching.

this wind profile and the occurrence of the squall lines (indicated by arrows) is illustrated in Fig. 2. Even though active convection organized into bands or lines was observed on 12 of the 16 days studied, moving squall lines occurred only when the low-level wind maximum was present (in both components when the squall lines moved from the northeast, but only in the northerly component on the 16th when the motion was from the north). The squall lines on the 4th, 11th and 12th moved about 1 m s\(^{-1}\) faster than the low-level maximum wind speed and therefore faster than the wind at any level in the troposphere, with inflow ahead and outflow to the rear, consistent with the radar picture of a sharp leading edge and trailing echoes behind. On the 16th the wind speed exceeded the propagation speed over a layer between 1.5 and 3 km but there was still low-level inflow ahead and higher-level outflow behind the system. The wind component along the lines was less than 5 m s\(^{-1}\) and almost constant up to 9 km; above this level the wind increased with height towards the right of the direction of travel.

The heights of cloud tops have been difficult to ascertain from the radar due to Oceanographer’s pitch stability problems and the fact that the squall lines were close to extreme range from Quadra. This meant that maximum echo heights displayed were liable to be inaccurate and often obscured by closer, possibly higher echoes. However, where data are available the maximum echo heights seem to be close to cloud tops as determined from the ordinary parcel theory, around 14 km, on the 4th, 11th and 12th. On the 16th the maximum echo heights are well below the parcel value for cloud top. A summary of the properties of these squall lines is shown in Table 1.
TABLE 1. Summary of the properties of the squall lines

<table>
<thead>
<tr>
<th>Date</th>
<th>Time of arrival of squall (GMT)</th>
<th>Length of squall line (km)</th>
<th>Lifetime (hrs)</th>
<th>Speed of travel (m s⁻¹)</th>
<th>Direction of travel (from)</th>
<th>Max. tropospheric wind before squall (m s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Sept.</td>
<td>1320</td>
<td>&gt; 250</td>
<td>14</td>
<td>12.7</td>
<td>045°</td>
<td>11.5</td>
</tr>
<tr>
<td>11 Sept.</td>
<td>1930</td>
<td>300</td>
<td>&gt; 6</td>
<td>16.0</td>
<td>053°</td>
<td>15.0</td>
</tr>
<tr>
<td>12 Sept.</td>
<td>1255</td>
<td>300</td>
<td>&gt; 9</td>
<td>15.1</td>
<td>045°</td>
<td>14.8</td>
</tr>
<tr>
<td>16 Sept.</td>
<td>0615</td>
<td>250</td>
<td>14</td>
<td>4.5</td>
<td>350°</td>
<td>10.0</td>
</tr>
</tbody>
</table>

3. The modification of the environment

Except on the 16th, comparisons of the soundings before and after the passage of the squall lines show differences which are in the same sense in each case and larger than the changes in a similar time interval before the arrival of the squalls. These differences can therefore be associated with the transport of heat, water vapour and momentum by the systems. The implied transports were similar to those of the Venezuelan storms described by Betts et al. (1976).

The squall line on the 16th had little discernible effect on its environment. It did, however, produce equally strong radar echoes and more rain at Oceanographer and Researcher compared with the other systems, the latter probably because it moved much more slowly. From now on discussion will be restricted to the squall lines on the 4th, 11th and 12th.

Fig. 3(a) shows the average flow in the direction of propagation relative to the squall lines, before and after passage over Oceanographer. There is an increase in momentum below the maximum wind level and a decrease above as observed by Betts et al. In the high troposphere there is an increase in the relative wind, presumably associated with the high-level outflow. The relative flow towards the squall line from the rear reported by Betts et al. is here more a region of small relative motion. This is more in agreement with the numerical simulation of Moncrieff and Miller, in which there is outflow behind at all levels in the mature stage. Whereas in Betts et al. the sample may have contained systems in different

![Figure 3](image-url)  
Figure 3. (a) Relative flow perpendicular to the squall lines before (solid lines) and after (pecked lines) passage of the squall. (b) As (a) but component along the lines.
stages of development, these squalls were mature as they had been well developed several hours before reaching Oceanographer and continued to be active for several hours afterwards.

The change in the component along the lines was not so consistent in the three cases and also varied more with height. The average change was very small up to 8 km (Fig. 3(b)) and the decrease shown above this level occurred in only two of the three cases.

The change in wet-bulb potential temperature is shown in Fig. 4(a) and except near the surface and in the high troposphere, is dominated by the mixing ratio changes shown in Fig. 4(b). There was an average temperature decrease of about 1.5 K in the lowest kilometre but above this level the changes differed in each case. On the 4th there was a cooling of about 0.5 K up to 6 km and a warming of about 1 K between 6 and 10 km. This high-level warming was also apparent on the 11th and weak on the 12th. On the 11th and 12th there was an increase in temperature and decrease in mixing ratio between 1 and 3 km consistent with descent behind the squall line. Miller and Betts (verbal communication) have found this in numerical simulations and associated it with descent above the spreading of a cold density current at the surface. Here the warming and drying continued for at least 2 hours after the squall had passed (and therefore for more than 100 km behind the squall line). However, rings or arcs of convection with a diameter a few times this value, perhaps marking the edges of cold outflows, can be observed from satellite pictures of the GATE area on many occasions.

4. Conclusion

The moving squall lines observed in the GATE area are similar to those observed more frequently over land. The structure and transports of heat, water vapour and momentum are consistent with the dynamical model and numerical simulations of Moncrieff and Miller. The close association of the low-level wind maximum with the squall lines suggests it may be a necessary condition for their development. Miller and Betts (verbal communication) find that the speed of movement of squall lines over Venezuela is allied with the speed of advance of the gravity current formed by the cold outflow. Over the tropical ocean this close association is not easily checked as the large inputs of sensible and latent heat from the surface rapidly modify the cold outflow. The role of the density current could be investigated using data from the various tethersonde systems deployed in GATE. Further work will involve the investigation of the more numerous semi-stationary bands and lines, to try to resolve the part played by larger-scale processes, through the ambient wind field and low-
level convergence, and that played by smaller scales such as density currents in determining their structure and motion.

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**References**

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