A Case Study of GATE Convective Activity

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ABSTRACT *This paper presents the synoptic and meso-scale aspects of the intense convective activity of 2 September 1974 in the Eastern Atlantic. Two main features were evident in the GATE B-scale array: a broad convective band associated with the 700-mb trough, and long and narrow lines of convection oriented SE–NW. One of these lines, which moved across the B-scale array and was penetrated by several aircraft, is described in detail. The structure of the cloud and precipitation fields, obtained from the analysis of satellite and radar data, indicates that intense precipitation occurred mainly at the leading edge of the line where new cells were continuously generating. Cross-sections through the line (from boom, aircraft and tethered balloon data) show a gust front at the surface, a downdraft region associated with the rain area, and a wind shift in the lowest 300 m. The circulations around and within this line appear to be similar to a class of tropical squall-lines studied at length by Zipser,*

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(1977) and Houze (1977) with the important difference that the horizontal gradients of the dynamic and thermodynamic variables across the line were typically weaker.

RÉSUMÉ *Cet article décrit les aspects d'échelle synoptique et moyenne de l'intense activité convective qui s'est développée le 2 Septembre 1974 dans la partie est de l'Atlantique. Deux configurations principales étaient présentes dans la région de l'échelle B: une large bande de convection associée au creux de la 700 mb, et plusieurs lignes de convection, longues et étroites, orientées suivant la direction sud-est nord-ouest. Une de ces lignes, qui s'est déplacée à travers la région de l'échelle B et à l'interieur de laquelle plusieurs avions ont pénètré, est décrite en détail. La structure des champs de nuage et de précipitation, obtenues à partir de l'analyse de données satellitaires et de radar, indique que les précipitations intenses eurent lieu principalement dans la région avant de la ligne où de nouvelles cellules étaient continuellement générées. Des sections transverses à travers la ligne (obtenues à partir de données de boom, d'avions et de ballons captifs) indiquent la présence d'un front de rafale à la surface, d'une région de courants descendants associéé à la région de pluie, et d'une ligne de discontinuité de direction du vent dans les 300 premiers mètres. Les circulations existant autour et à l'intérieur de cette ligne semblent être similaires à celles d'une certaine classe de lignes de grain tropicales étudiées en détail par Zipser (1977) et Houze (1977) mais avec la différence importante que les gradients des variables dynamiques et thermodynamiques à travers la ligne étaient, dans le cas du 2 Septembre 1974, typiquement plus faibles.*

1 Introduction

This paper is intended to provide a descriptive background to a series of papers concerned with the interaction of meso-scale convection with the large-scale environment in the Eastern Atlantic during GATE. The case study approach used in this paper is intended to complement composite studies (Burpee, 1975; Burpee and Dugdale, 1975; Reed et al., 1977) by showing in detail how individual disturbances differ from the large-scale ensemble average. Furthermore, case studies can provide important details on scales much smaller than those analyzed by composites of GATE disturbances presented thus far.

The case of September 2, 1974 (Julian Day 245) was chosen for study because of the coexistence of meso-scale lines of convection and a well-defined Inter-Tropical Convergence Zone (ITCZ) within the GATE ship network. This was a day of enhanced convection reaching a maximum intensity toward the end of the day. A N-S aircraft mission was flown near the C-scale array. The aircraft penetrated two meso-scale lines several times during their life cycles. A hierarchy of observations was available on different time and space scales, from satellite, radar, rawinsonde, aircraft, and tethered balloon. From these data sets we were able to construct a history of the formation and decay of line convection over the GATE A/B-scale array.

2 Synoptic and meso-scale aspects

September 2, 1974 was characterized by the progression of a 700-mb wave disturbance over the B-scale ship array. This wave disturbance has been

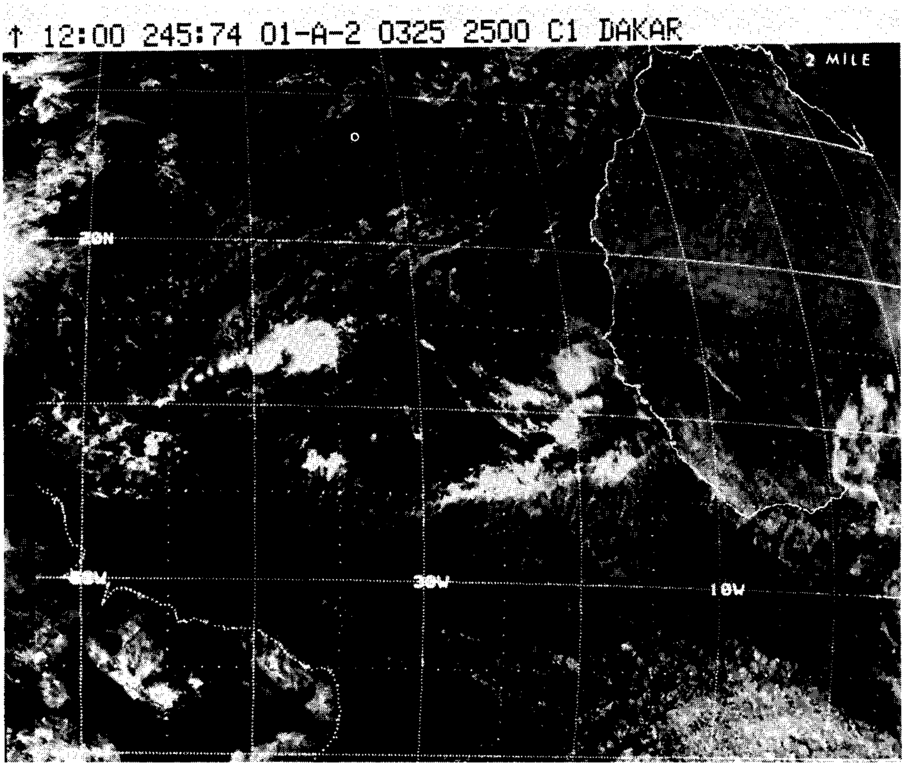


Fig. 1 Visible SMS-1 satellite image for 1200Z, 2 September 1974.

included in a composite study by Reed et al. (1977). Fig. 1 shows the visible SMS-1 satellite image for 1200Z. Fig. 2 shows the 700-mb streamlines and simultaneous composite radar echoes within the B-scale ship array. The vertical line near 23°W in the figure denotes the aircraft tracks during the flight pattern (1130Z–1500Z).

The figures show that at 1200Z the convective activity preceded the 700-mb trough in general agreement with the results of Reed et al. (1977). Later in the day, around 1800Z, convective activity was coincident with the trough. From 1200Z to 1800Z the trough moved westward at a speed exceeding 10 m s^{-1}; from 1800Z to 2400Z the mean speed was about 5 m s^{-1}.

Two main features were evident within the B-scale array: a broad convective band which was part of the ITCZ associated with the 700-mb trough; and long (300 km), narrow (20–30 km) lines of convection oriented WNW-ESE perpendicular to the mean flow. From 1200Z to 1800Z the long lines moved southwestward at a speed of approximately 6 m s^{-1}.

Surface streamlines were analyzed hourly from 1000Z to 1800Z. The GATE A- and B-scale ship data set was used in conjunction with radar echo maps and low-level aircraft winds. Fig. 3a shows the 1200Z analysis. A cyclonic shear line was evident near 9°N with two convergence lines farther to the south. The shear line was closely associated with the line of convection which first

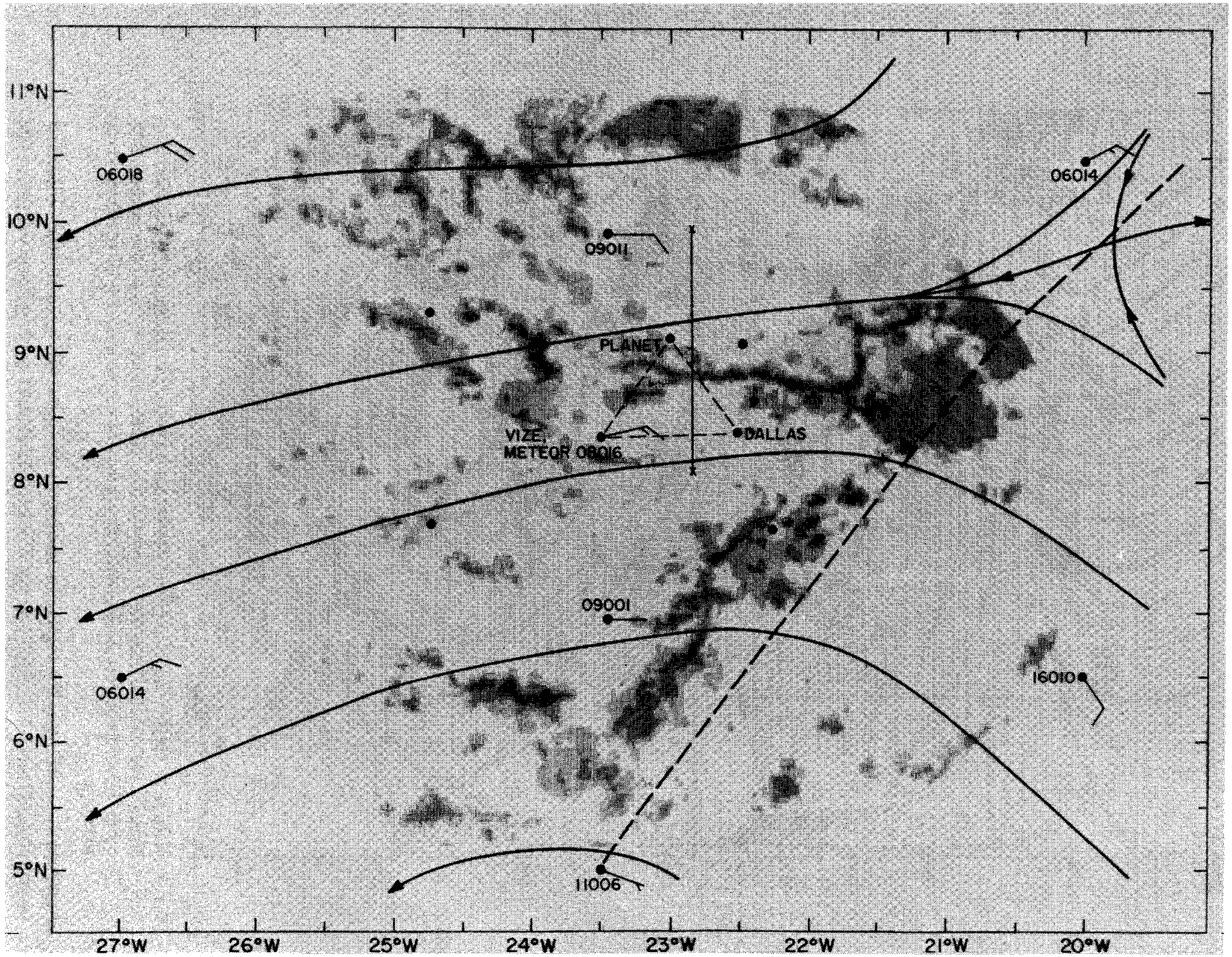
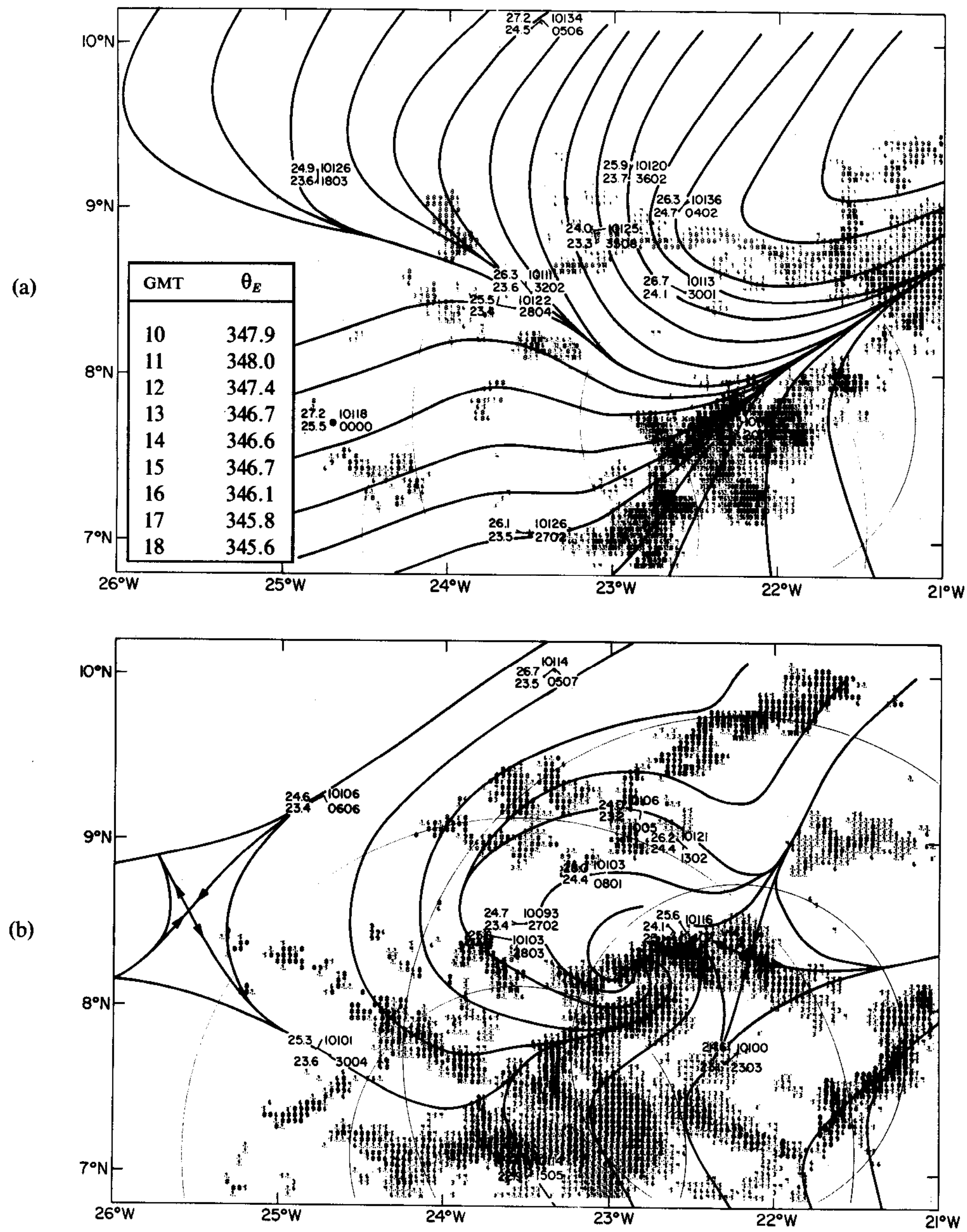


Fig. 2 700-mb steamline analysis superimposed on composite radar echoes from the *Oceanographer, Researcher, Gillis*, and *Quadra* for 1200Z. The gray shades correspond to rainfall rates of 0.05, 2.0, and 14.0 mm h^{-1}. The vertical line denotes the aircraft tracks during 1130 to 1500Z. The C-scale ship triangle is indicated.



GMT	θ_E
10	347.9
11	348.0
12	347.4
13	346.7
14	346.6
15	346.7
16	346.1
17	345.8
18	345.6

Fig. 3 Surface streamline analysis for (a) 1200Z and (b) 1600Z, using the WMO data set. The hybrid radar data are from the *Oceanographer* and *Researcher*. Inset table on the 1200Z maps shows the change of mean equivalent potential temperature with time over the area of map analysis.

appeared on the *Quadra* radar far to the north (near 10°N) at 0530Z. This line moved south and at 1300Z merged with the broad area of convection (see extreme right of Fig. 3a). At 1230Z a second line formed to the north of the line of interest and lasted a few hours.

By 1600Z, surface streamlines (see Fig. 3b) revealed a low-level meso-scale circulation which passed through the southern part of the C-scale array. During the development of the circulation the broad convective band and the narrow convective lines became less well defined as convection formed irregularly over the B-scale array. Radar echoes shown in the lower right of Fig. 3 moved from the south while the echoes in the western section moved from the northeast. This meso-scale vortex motion persisted through 1800Z (last map time analyzed).

The *Gillis* radar, to the west of the C-array, showed similar cyclonic motion, propagating westward well into the early morning hours of 3 September. This feature was tracked for several days across the Atlantic by Sadler (1977).

The insert of Fig. 3a shows that over the period 1000Z to 1800Z the mean equivalent potential temperature (θ_E) at the surface decreased with time. This decrease of 1 to 1.5 K is well correlated with an increase of radar echo in the analysis area indicating the presence of downdraft air in the echo region. θ_E was generally low over the entire analysis time, its mean value never exceeding 347 K, (individual values were as high as 352 K) yet meso-scale convection increased. Low θ_E air persisted from the surface to at least 575 m. The mean θ_E at 950 mb was 342 K (5 K lower than at the sea surface). Low θ_E air implies that strong subcloud layer convergence was needed to maintain the convective activity.

In order to compare the independent data sets which will be combined for detailed analysis, the 950-mb streamline chart for 1200Z was drawn. This height was chosen to correspond to the low-level cloud motion field derived from SMS-1 satellite data, winds from the NCAR Electra and winds derived from ship BLIS*. These independent data sets mesh together very well as shown in Fig. 4. The cyclonic shear line extending from the *Dallas* to the *Gillis* is nearly coincident with the surface shear line and the line of convection positioned by satellite and radar imagery. Another shear line to the south of the C-array does not appear to be associated with precipitating cloud except near the *Oceanographer* (8°30′N, 23°30′W) and *Bidassoa* (7°45′N, 24°48′W).

3 Line convection in the meso-scale flow

Attention is now focussed on some dynamic and thermodynamic features of the line which intercepted *Quadra* at about 1200Z. The structure and flow relative to the line has been inferred from a series of cross-sections derived from aircraft and BLIS data.

a *Satellite and Radar Description of the Line*

Loops of radar data from *Oceanographer* and *Quadra* indicate that small cells appeared to the northeast of the B-scale array at 0530Z. They were organized into two parallel E-W lines, separated by 30 km. The lines strengthened and moved SSW at about 6 m s^{-1}. Echoes linking the lines, oriented NW–SE,

*Boundary Layer Instrument System on *Dallas*, *Oceanographer* and *Researcher*.

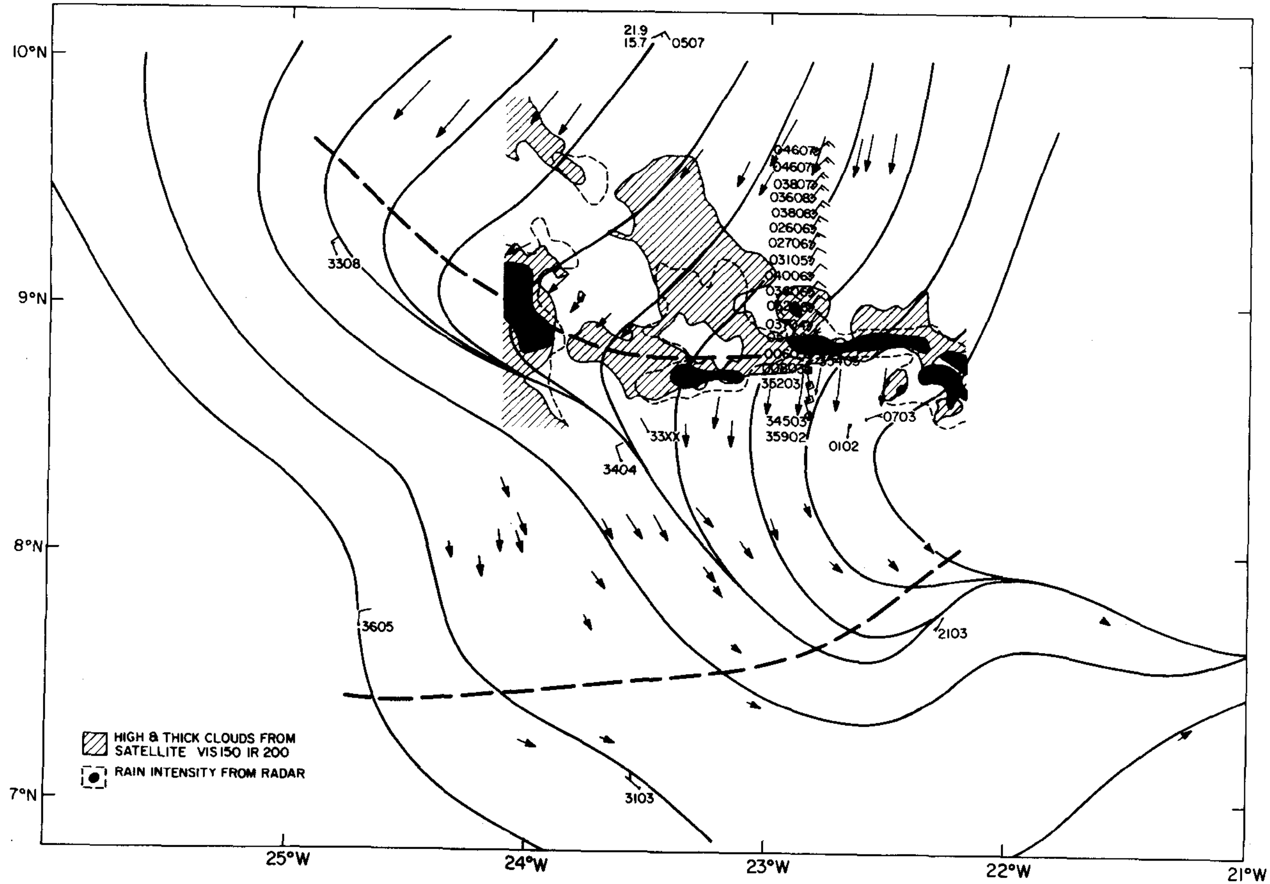


Fig. 4 950-mb steamline analysis at 1200Z. Wind data from the Electra aircraft is indicated with a box; arrows denote low-level cloud motions from the SMS-1 satellite data; other winds are from the ship BLIS data. Hatched areas correspond to deep convection deduced from combined digital visible and IR satellite data. Dashed lines show radar echoes above minimum detectable signal; dark regions indicate rainfall rates 10 mm h^{-1} from the *Quadra* radar.

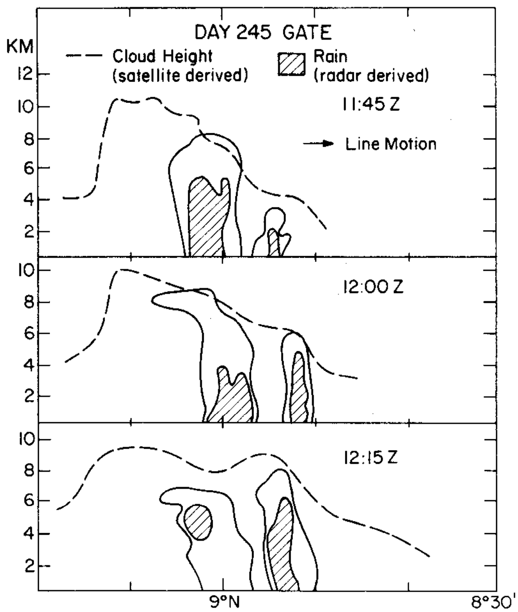


Fig. 5 Cross-sections through the convective line at 22°51′W longitude, along the aircraft flight tracks on 2 September 1974. Radar data were obtained from *Quadra*.

formed between the lines at 0900Z. By 1200Z, the lines merged to form one line which extended from the ITCZ band 200 km to the east of *Quadra*, as far as the *Gillis* – a distance of about 400 km. Satellite images for that time show that the cirrus outflow from the line was linked by NW–SE "bridges" to the convective activity located at its leading edge. Between 1200Z and 1500Z the east part of the line gradually merged into the ITCZ. By this time a second line formed about 60 km to the north of the *Quadra*.

An interesting feature of the first line is its convex curvature as viewed from the south in its initial growing phase, constrasting with its linear form near 0900Z and its concave shape near the end of its life cycle.

Both satellite and radar images show that the line consists of discrete convective cells several kilometres in diameter, their heights depending on their stage of development (between 3 and 10 km). The convective and precipitation fields at 1200Z are presented in Fig. 4. The hatched areas show regions of deep and active convection as deduced from a combination of digital visible and infra-red satellite data using a program developed at the University of Wisconsin. The dashed contours indicate the rainfall region obtained from the raw *Quadra* radar data (above minimum detectable signal). Intense precipitation (darker regions corresponding to rainfall rate greater than 10 mm h^{-1}), occurred mainly at the leading edge of the line. There was also some light precipitation falling from a relatively thick cirrus anvil which was itself a product of the individual convective cells.

A series of cross-sections through the line at 22°51′W (along the aircraft track) are shown in Fig. 5. The cross-sections are for a 30-min period centered on 1200Z. This figure shows the evolution of the precipitation cells, together

TABLE 1. Flight altitudes for the GATE aircraft on Day 245

Aircraft Type	Altitudes (km)	Pressure (mb)
DC-6	0.85, 1.3, 2	985, 970, 945
L-188	3.2, 6	900, 810
US C-130	9, 12	720, 640
IL-18C	15	574
CV-990	25, 27, 31	380, 290, 220

with the cloud tops (dashed lines) obtained from the combined satellite data (visible and infra-red). Rain cells formed at the leading edge of the line and grew rapidly to a mature stage. They then began to tilt northward forming light, widespread precipitation below the anvil. In their early stage of development, the cells appeared to move rapidly southward, but to decelerate as they reached maturity.

Fig. 5 shows two cells going through their life cycle simultaneously, separated by a region of no precipitation. This structure was also evident from aircraft measurements.

b *Aircraft and BLIS Data*

The principal data for the study of the line were obtained from the aircraft and BLIS. Five aircraft traversed the line repeatedly at several times. Table 1 gives the flight altitudes of the five aircraft for which data were available.

With the exception of the CV-990 and IL-18C, parameters were recorded every second throughout the flight and these data were averaged in ten-second blocks, giving a horizontal space resolution of approximately 1 km.

The BLIS data set consisted of wind, temperature and humidity measurements taken in the subcloud layer from the ship's boom (surface) and tethered balloon (995, 970, 950 and 910 mb). These data have been averaged in three-minute blocks.

c *Line Location*

The leading edge of the line has been located in a qualitative sense from the radar and satellite images. However, before data could be composited, the line had to be located more accurately in space and time. Because the aircraft were flying at different altitudes they traversed different parts of the line. For example, the DC-6, which was flying near the surface, traversed the surface gust front on each pass. The wind data from this aircraft yield a fix on the gust front. Using each successive pass, the progression of the gust front was monitored. Similarly the CV-990 traversed the towers on each pass. These and other features of the line were plotted against latitude and time (Fig. 6). A line of least squares fit has been computed, the slope of which yields a mean travel speed of 6.1 m s^{-1}. Physically, the least squares fit corresponds to a

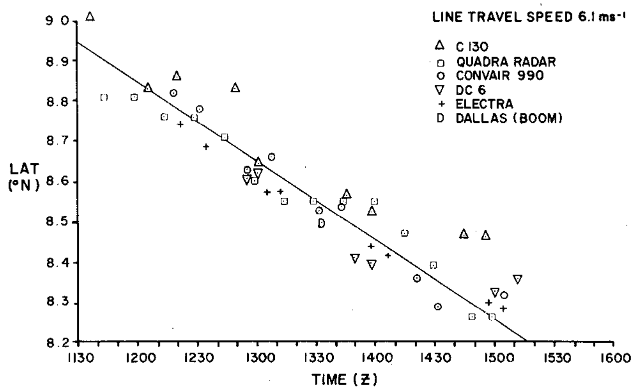


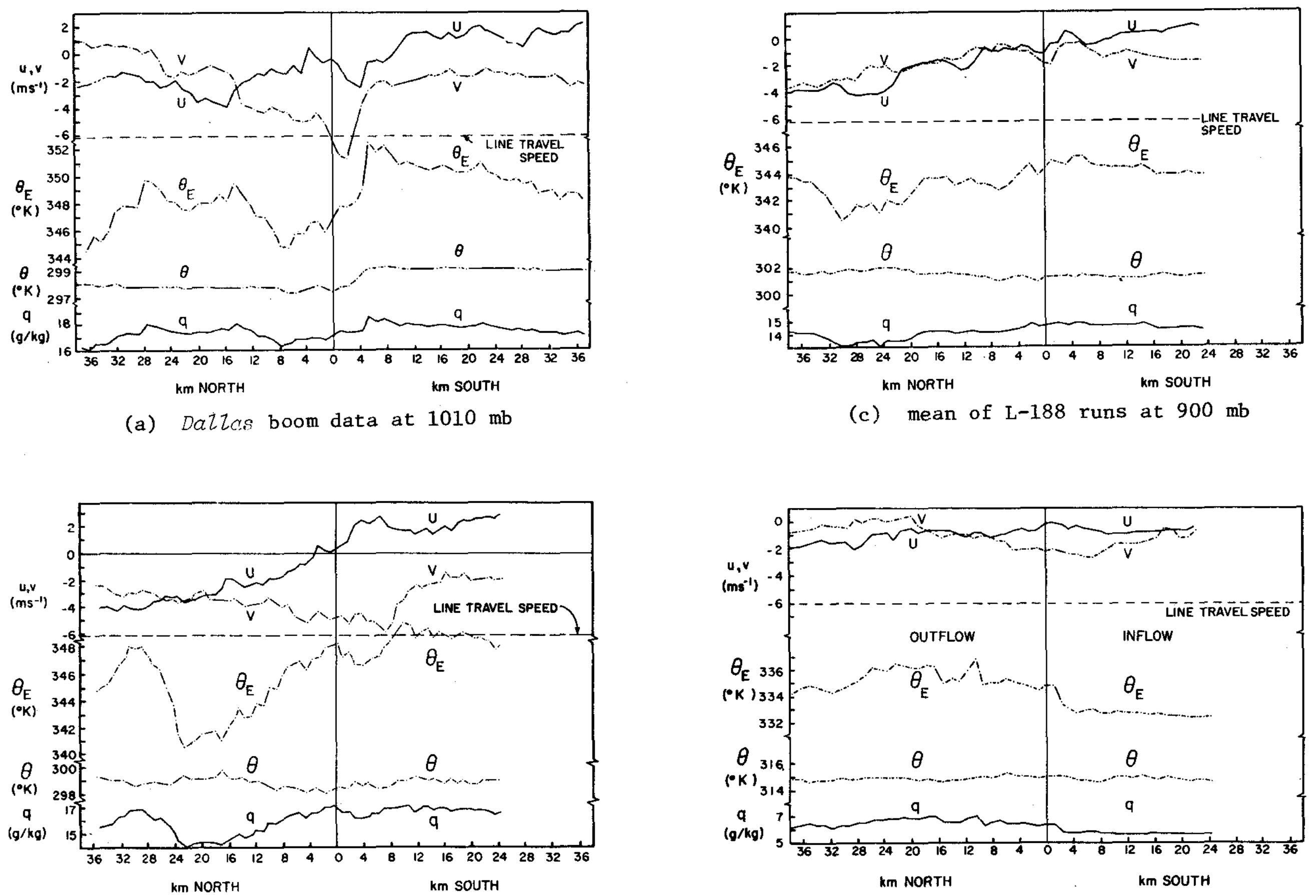
Fig. 6 Convective line passage as a function of latitude and time, 2 September 1974. Slope of the line of least squares fit indicates the mean travel speed of the convective line.

plane in space located between the gust front and the towers. In subsequent figures, the data have been plotted relative to this plane.

d *Cross-Sections Through the Line from Boom and Aircraft Data*

Cross-sections for the surface, 985, 900 and 640 mb are shown in Fig. 7a–d. Distances in kilometres to the north and south of the plane of least squares fit are indicated on the abscissa. Figure 7a shows the passage of the line over the *Dallas* at 1330Z. A large drop in θ_E of 7 K at the time of line passage is evident. At this (surface) level the drop is a combination of both cooling (1.5 K) and drying (2 g kg^{-1}). Figs 7b and 7c show a similar trend in θ_E, but at these levels there is no observable temperature change across the line. The local minimum in θ_E at about 20 km north of the line was readily associated with a downdraft, the origin of which will be discussed in the next section. At 640 mb (Fig. 7d) the trend in θ_E is in the opposite sense in that the air to the north has a higher θ_E. This is due to a gradual rise in specific humidity (q) resulting from meso-scale ascent behind the line. Super-imposed on the general trend in θ_E (or q) in the outflow at this level are one or two local maxima associated with growing cumulus towers.

There are also several interesting features in the wind data. At the surface, the v-component of the wind changed by 6 m s^{-1} in 9 min. This sharp change denotes the onset of the surface gust front. The two-dimensional convergence at the front was approximately 1.4×10^{-3} s^{-1} assuming a space-time conversion of 6.1 m s^{-1}. This wind shift was also evident at 985 mb, although of smaller magnitude. At levels higher than this, there was no evidence of a wind shift. The difference between the v-component and the line travel speed indicates about 4 m s^{-1} of inflow into the line from the south and a similar magnitude of outflow to the north. The gust front travelled close to the mean speed of the line. The u-component was also interesting, because to the south of the line it was positive (westerly) and to the north of the line it was negative (easterly). This occurred up to about 800 mb. The two-dimensional cyclonic vorticity across the line was approximately 1.6×10^{-4} s^{-1}.



(a) *Dallas* boom data at 1010 mb

(b) mean of DC-6 runs at 986 mb

(c) mean of L-188 runs at 900 mb

(d) mean of U. S. C-130 runs at 640 mb

Fig. 7 Time series relative to convective line passage, 2 September 1974.

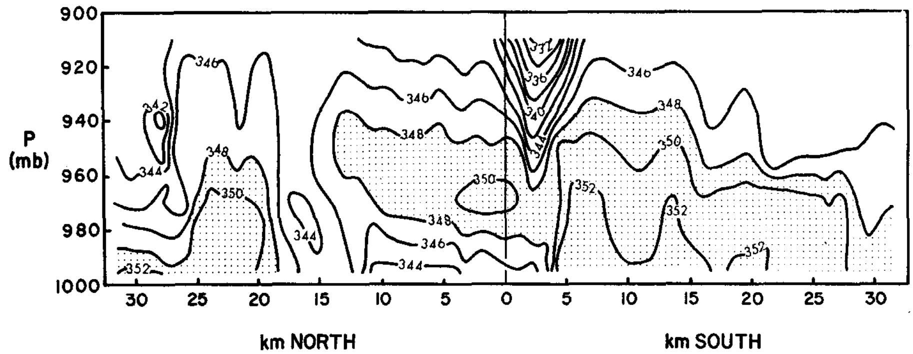


Fig. 8 Equivalent potential temperature relative to the convective line passage on 2 September 1974. Data for this cross-section are from three-minute *Dallas* BLIS data.

e *Cross-Section Through the Line from Tethered-Balloon Data*

By translating the time scale (3 min) into a space scale (1.1 km) the three-minute tethered-balloon data have been plotted relative to the line at four levels. The shaded area in Fig. 8 denotes the extent of the warm, moist air which fed into the line from the south. About 15 km to the rear of the line was a local minimum in θ_E. This was the downdraft which was shown in Fig. 7 a–d. This downdraft spread southward as it reached the surface and terminated at the gust front. The front appeared to force air out of the subcloud layer into the main updraft. Assuming the air parcels conserved θ_E in descent, a likely source for the downdraft is the air between 900 and 800 mb ahead of the line. The tongue of anomalously low θ_E values immediately to the south of the line is probably fictitious. Hygristor values were used to compute θ_E but the top two instruments appear to have been affected by precipitation. The thermistor wet-bulb values (which were not available) may be more reliable in this case. The other features shown in the cross-section agree with the aircraft and boom data.

The wind components from the *Dallas* boom and the aircraft have been averaged in the inflow and outflow regions at all eleven levels (Mower, 1977). The vertical profiles thus obtained showed the line to be embedded in an almost unsheared environment below 400 mb. Also, there was no evidence of a steering level. The line appeared to propagate through the environment, driven by purely convective processes. The environmental wind field, in the vicinity of the line (~30 km either side), was convergent and cyclonic from the surface to about 750 mb.

4 Discussion

This subsection will focus on the points which have emerged from this preliminary analysis.

a *Large-Scale and Meso-Scale*

The convection over the GATE A/B-scale array was strongly associated with the trough of a synoptic-scale easterly wave which was tracked across the Atlantic Ocean for several days. The broad band (ITCZ) preceded the 700-mb trough during its growing phase and the trough speed was greater than the zonal wind speed. These observations are consistent with the composite study of Reed et al. (1977), and can be related to Riehl's (1954) simple dynamic model of an easterly wave in the tropics.

Over the entire B-scale array the mean θ_E near the surface was generally low (~347 K) during the study period even though convective activity increased. The stability in the region is currently under investigation to determine the degree to which dynamical forcing was responsible for the convection.

A meso-scale vortex associated with the 700-mb trough was observed during the intensification of convective activity. The formation of this vortex, and its relationship to convective activity, is a subject for future research.

b *Line Convection*

The southern line of convection, studied in detail in this paper, appears to be similar to tropical squall lines of the type discussed in Miller and Betts (1977), Zipser (1977) and Houze (1977) but with some important differences:

1. The N-S changes in θ, u and v were smaller than the changes observed in squall lines and were confined to the lowest 300 m as opposed to several hundred millibars. The change in q (caused by low-level drying, with moistening above) was also smaller.
2. Below 400 mb there was little vertical wind shear, and no tilt was observed in the individual convective cells.
3. The downdraft originated in the lower troposphere.
4. The propagation velocity was small (6 m s^{-1}).

The formation of a second line 60 km to the rear of the southern line implies that advection augmented surface fluxes in the recovery of the sub-cloud layer in the wake of the line.

Acknowledgements

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