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Structure of a northern Australian squall line system

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A study is presented of a major squall system which affected large areas of northern Australia during 3-5 January 1981. At Darwin, this system produced a record January wind gust of 37 m s^{-1}. The large-scale environment in which the squall system developed is described and some factors contributing to its formation are detailed. The mesoscale structure of the system at the time of its passage through Darwin is examined within the framework of the models developed by Zipser (1977) and Houze (1977). The extreme wind gust is attributed to a 'microburst' as described by Fujita (1978).

Introduction

A severe squall line, with an extreme wind gust of 37 m s^{-1} (72 knots), passed through Darwin at 1700 UTC 4 January 1981. This gust was the highest recorded since cyclone *Tracy* in December 1974, and higher than the maximum gust in cyclone *Max* which affected the city two months later in March 1981. Wind speeds exceeded 17 m s^{-1} for approximately half an hour and widespread minor damage was reported around the city.

The general conditions necessary for the development of severe convective storms have been described by Newton (1963). They include instability, low-level moisture, and a dynamic mechanism to release the instability. Additionally, Aspliden et al. (1976) found that a layer of dry air above the moist low-level air was favourable for the production of strong precipitation-evaporation downdraughts associated with squall lines.

The mesoscale structure of tropical squall lines has been well documented in recent years as a result of various meteorological experiments; the Line Islands Experiment (LIE), the Venezuelan International Meteorological and Hydrological Experiment (VIMHEX), and especially the GARP Atlantic Tropical Experiment (GATE). Atkinson (1981) presents a concise review of these studies.

Radar and satellite data, especially that from the Geostationary Meteorological Satellite (GMS), have shown that squall lines also exist over tropical northern Australia. Falls (1970) has briefly discussed the broadscale environment in which some of these systems form, but their mesoscale structure has not been documented.

Broadscale description of the squall system

The broadscale flow patterns over northern Australia at 0001 UTC 3 January 1981, approximately eighteen hours before the squall system formed, are shown in Fig. 1. At the surface the major features were a weak monsoon trough along 10°S, a heat low and trough over northern Australia, and a cold frontal system moving across southeastern Australia. Above the surface the dominant feature was a quasi-stationary cut-off low over southern Queensland.

The squall system developed between 1800 UTC and 2100 UTC 3 January in the southeast corner of the Gulf of Carpentaria and propagated in a west-northwest direction. The location of the leading edge of the squall line, as determined by GMS imagery and Darwin radar, is shown in Fig. 2.

The speed of movement of the leading edge of the system varied from 12 m s^{-1} at 0001 UTC 4 January to 21 m s^{-1} at 1700 UTC 4 January when it passed through Darwin. Average speed of movement during the 24-hour period from 0001 UTC 4 January to 0001 UTC 5 January was 14 m s^{-1}. Direction of motion, measured at the midpoint of the leading edge, remained more constant west-northwest (towards 300°) throughout this period.

The system eventually lost its squall line structure near 120°E after 0900 UTC 5 January.

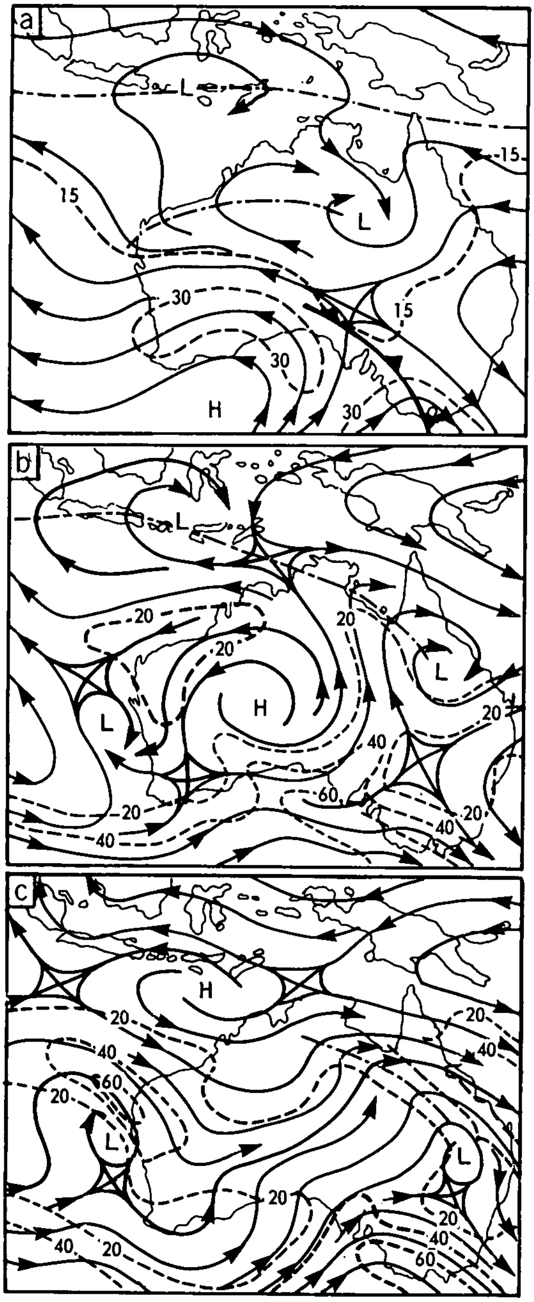
Mesoscale structure

Satellite and radar data

High resolution visual (HRVIS) GMS imagery for 0100 UTC and 0600 UTC are shown in Fig. 3. The squall system consists of a curved leading edge of cumulonimbus four to five degrees in length followed by a large area of altostratus and cirrus comprising the anvil remnants.

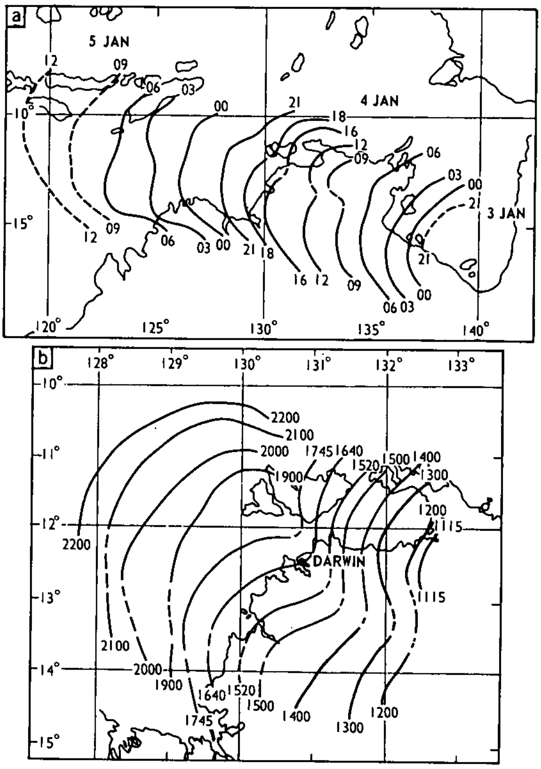
By 0600 UTC diurnal convection had developed along the north coast ahead of the squall system and interacted with it to produce the distortion in the leading edge evident from 0900 UTC until 1800 UTC

Fig. 1 **Broadscale streamline/isotach analyses for 0001 UTC 3 January 1981. (a) Gradient level (900m), (b) 500 mb, (c) 250 mb. (Isotachs in knots: 1 knot ≡ 0.51 m s-1)**



4 January. A similar enhancement of convective elements ahead of, and eventual incorporation into, a squall line has been observed in a GATE squall by Houze (1977).

Fig. 2 **Isochrones of leading edge of squall system based on (a) GMS imagery 2100 UTC 3 January to 1200 UTC 5 January 1981, (b) Darwin radar reports (RAREPS) 1115 UTC 4 January to 2200 UTC 4 January 1981.**



Darwin radar reports (RAREPS) from 1400 UTC to 1740 UTC 4 January are shown in Fig. 4. These show that this convection had formed a secondary line, orientated north-south ahead of, and moving westward more slowly than, the main squall line. Unfortunately the time resolution of these rareps is too coarse to determine the motion of individual convective elements within the leading edge.

Composite wind fields

To examine the synoptic/mesoscale wind fields in the vicinity of the squall system a composite analysis was constructed. This step was necessary due to the very sparse upper-air network in the region. The technique of compositing observations at different times to study mesoscale phenomena such as squall lines was developed by Fujita (1963), and is valid providing the system being studied remains in a 'steady state'. Changes in the observed winds are then due only to the passage of the system and not to changes in the internal structure. This assumption may be justified by the consistency of the resulting analyses.

These composite analyses (Fig. 5) were based on data for 1000 UTC 4 January with all observations up to twelve hours before and after this time added at the appropriate position relative to the midpoint

Fig. 3 High resolution visual (HR VIS) GMS imagery of the squall line system at (a) 0100 UTC 4 January 1981, and (b) 0600 UTC 4 January 1981.

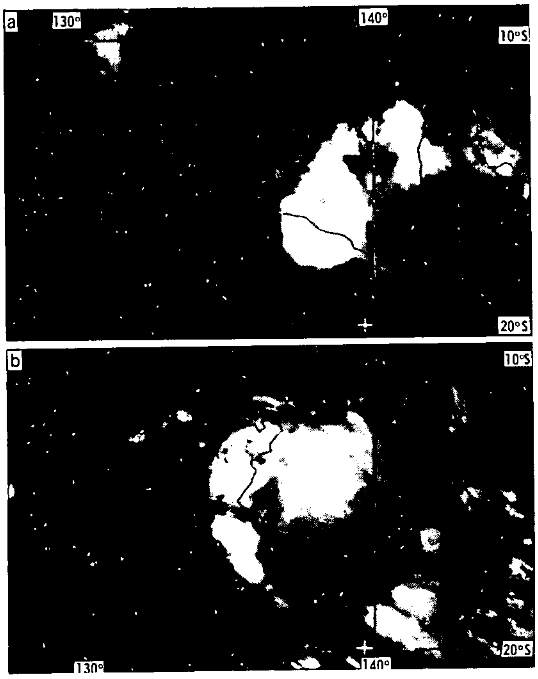


Fig. 4 Darwin Airport radar reports (RAREPS) (a) 1400 UTC, (b) 1520 UTC, (c) 1645 UTC and (d) 1745 UTC 4 January 1981.
Rainfall rates: solid 63mm/h, striped 28mm/h, open 7mm/h.

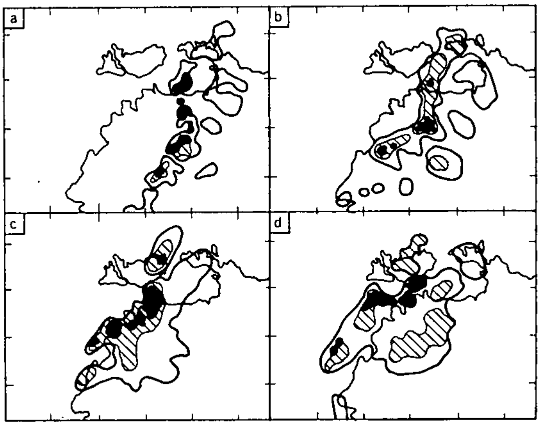
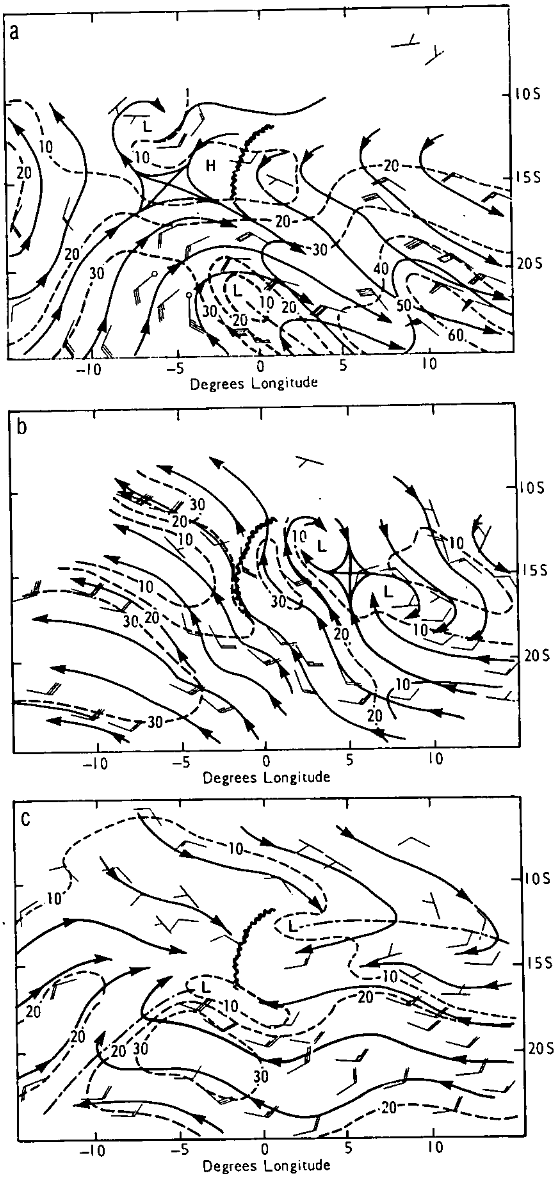


Fig. 5 Composite synoptic/mesoscale wind fields around the squall line system, based on 1000 UTC 4 January. (a) Upper level 250 mb, (b) Middle level 600 mb, (c) Low level 900 mb.
(Isotachs in knots: 1 knot ≡ 0.51 m s^{-1}.)



of the leading edge of the squall system. Eleven levels from the surface to 150 mb were analysed in this manner and revealed a three-layered structure.

At low levels (below 850 mb) the leading edge of the squall system lay along a confluence line between westerly flow ahead of, and easterly flow to the rear of the squall. In the middle levels (850 mb to 400 mb) the flow throughout the region traversed by the squall was southeasterly, with a local wind maximum immediately behind the leading edge and ahead of a trough which had extended northwest from the southern Queensland low. A weak secondary low may have formed on this trough under the anvil rain area.

The flow over the system at upper levels (400 mb to 150 mb) was strongly divergent. The trough evident at 250 mb at 0001 UTC 3 January (Fig. 1(c)) had become extremely involuted. The subtropical ridge lay almost directly over the squall system and the outflow accelerated into the northwesterly flow ahead of the trough, which retrogressed westward so that it remained five degrees ahead of the leading edge of the squall.

Comparison with other squall systems

Data recorded at Darwin Airport during the passage of the squall are presented in Figs 6 to 10. The meso/convective-scale model used in Fig. 6 is based on that presented by Zipser (1977). At the surface, three significant features are immediately apparent. Firstly there was an extremely rapid wind change, from light northwesterly to a strong and gusty southeasterly associated with the convective-scale downdraught.

The rapidity of this change is best seen in the anemographs from Darwin Airport (Fig. 7). The larger mesoscale wind change was then to a northeasterly, as is evident on the low-level composite wind analysis (Fig. 5(a)). Secondly a marked pressure rise of approximately 1.5 mb occurred within ten minutes of the squall front passage (the convective-scale downdraught). Pressure continued to rise slowly for another 30 minutes to a peak of approximately 2.5 mb above the pre-squall level (the mesoscale high). This was followed by a gradual fall to the meso-low at the end of the light rain from the anvil. Thirdly, temperature and dew-point dropped from 29 °C and 24 °C before the squall to a minimum of 21 °C and 20 °C approximately half an hour after passage of the squall front. The temperature gradually rose to 27 °C at the meso-low, but the dew-point remained low at 22 °C.

Radar wind soundings are performed routinely at Darwin at 0400, 1000, 1600 and 2200 UTC. The vertical wind profiles at 1600 UTC 4 January and 2200 UTC 4 January, immediately before and after the squall, are shown in Fig. 8, resolved into components normal and parallel to the direction of motion of the squall. Relative to the squall these profiles show strong low-level westerly inflow before the squall

Fig. 6 Proposed structure of squall system in the vicinity of Darwin, based on Zipser's model (1977). Pressure, temperature and dew-point curves, and surface winds derived from half-hourly airport weather reports (METARS). All winds are shown relative to squall (moving towards 300 degs at 14 m s^{-1}). (Full barb 10 knots ≡ 5 m s^{-1}, half barb 5 knots ≡ 2.5 m s^{-1}.) Cumulative rainfall and rainfall rates were determined from Darwin Airport pluviograph record.

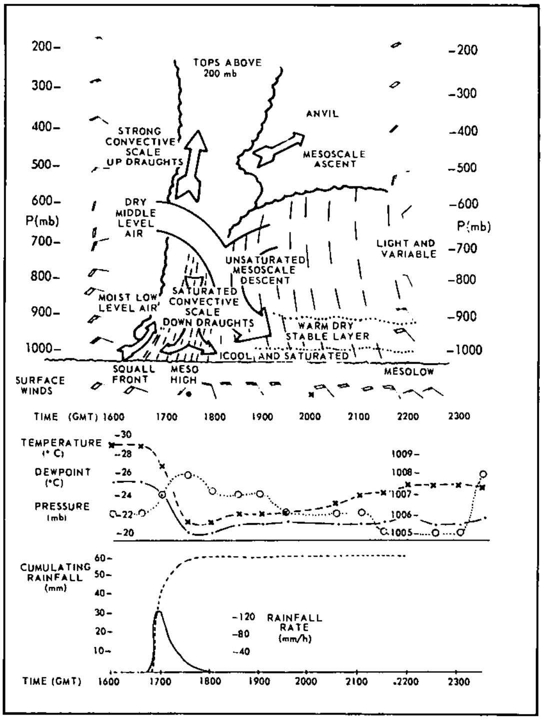
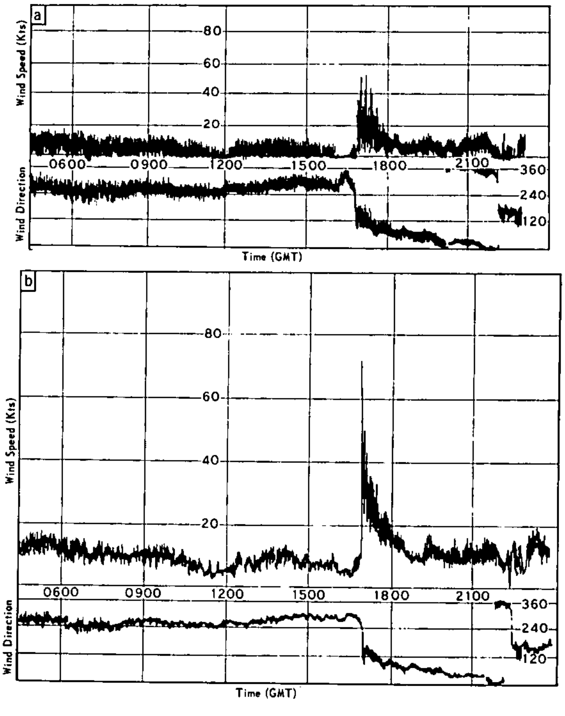


Fig. 7 Anemograph records from Darwin Airport.
(A) High-speed Dines located at Darwin Airport Meteorological Office, (B) Low-speed Dines located at Darwin Airport Weather Service Office (1.5 km NW of A).
Upper panel: wind speed in knots
Lower panel: wind direction in degrees from true north.
(Later calibration showed that instrument A (high speed) under-estimated light winds (less than 8 m s^{-1}) by up to 3 m s^{-1}. Above 10 m s^{-1} both instruments gave accurate readings.)



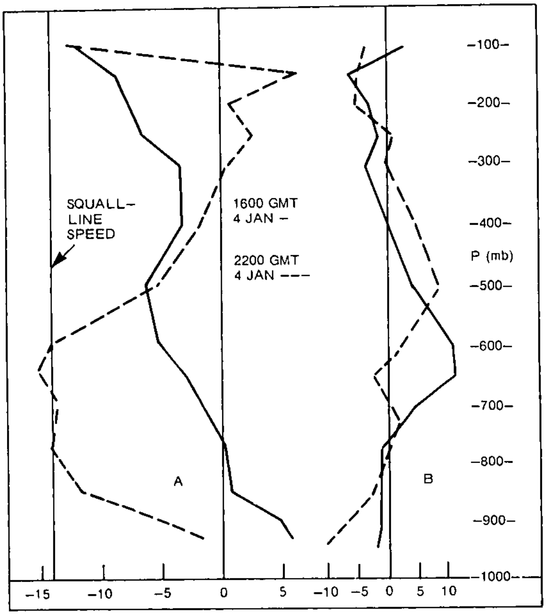


Fig. 8 **Vertical wind profiles at Darwin Airport before (1600 UTC 4 January solid) and after (2200 UTC 4 January dashed) the squall resolved into components.**
(A) parallel to direction of motion of the squall (positive towards 120°), (B) normal to direction of motion of the squall (positive towards 030°).
(Squall orientated 030°-210° and moving towards 300° at 14 m s^{-1}.)

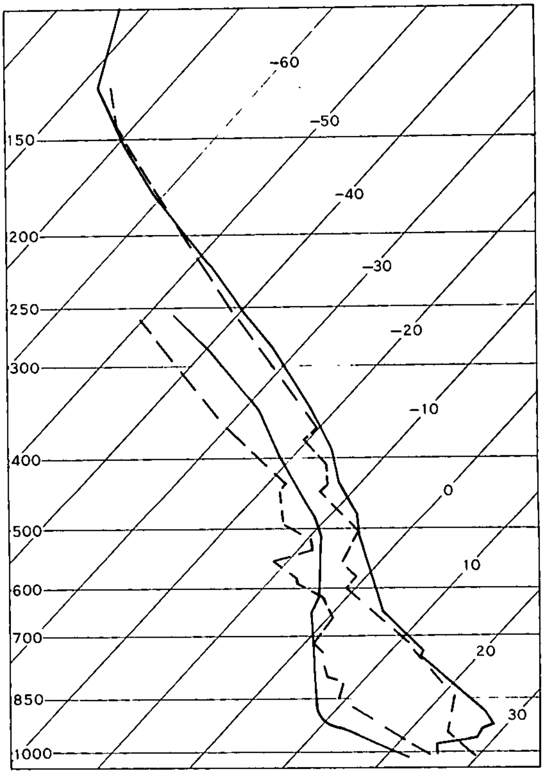


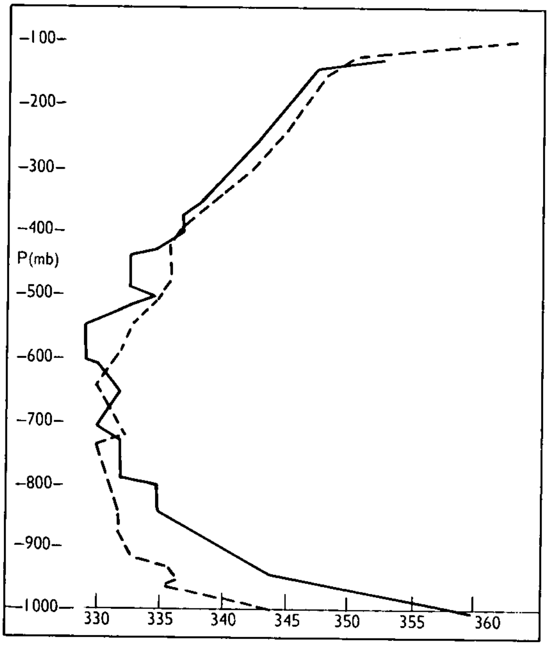
Fig. 9 **Tropospheric temperature soundings at Darwin Airport.**
Pre-squall 2200 UTC 3 January (dashed)
Post-squall 2200 UTC 4 January (solid).

front, upper-level westerly outflow well behind the squall front, and middle-level southeasterly flow both before and after the squall. The squall propagated at a greater speed than the environmental air, both before and after the squall, apart from the layer between 800 mb and 600 mb where the wind speed behind the squall was approximately the same as the squall's speed.

Upper-air temperature soundings are performed only once daily, at 2200 UTC, so that only soundings nineteen hours before and five hours after the passage of the squall are available. Since the squall was the only weather system to affect Darwin during this period, these soundings, shown in Fig. 9, may be representative despite the large time lapse. The pre-squall sounding showed the usual moist, convectively unstable structure typical of the tropics during the pre-monsoon transition season. The post-squall sounding, taken at the end of the light rain behind the squall front, has the 'diamond' or 'onion' shape described by Zipser (1977) as being typical of post-squall conditions. This sounding consists of a cool, nearly saturated surface layer (top at 970 mb) separated from warm dry air above by a marked stable layer (970 mb to 910 mb). The dew-point depression at the top of this stable layer is 17.3 °C and the relative humidity only 32 per cent. The onion shape is completed in middle levels where the dew-point depression decreases to below 5 °C around 550 mb, which is the base of the reported altostratus overcast. This difference in low-level air masses is more noticeable in the profile of static energy, which can be approximated by the pseudo-equivalent potential temperature Θse (Fig. 10). Behind the squall front there was a marked decrease on Θse and hence in static energy below 800 mb.

These wind and static energy profiles are almost identical to those presented by Miller and Betts (1979) who composited data around a series of travelling convective storms in Venezuela during VIMHEX. Zipser (1977) and Houze (1977) attribute this post-squall thermo-dynamic structure to the presence of two distinct downdraught systems, one on the convective scale which produces the cool saturated surface layer, and a mesoscale downdraught beneath the anvil which remains unsaturated and produces the warm dry layer. Gamache and Houze (1982) have composited upper wind data around a GATE squall line and confirmed the existence of these two systems; the convective scale squall line and the mesoscale anvil, with their own up and down-draught systems. In the mesoscale, convergence in the middle levels (around 600 mb) drives both an updraught wi-

Fig. 10 Pseudo-equivalent potential temperature Θse at Darwin at 2200 UTC 3 January 1981 (solid, pre-squall) and 2200 UTC 4 January 1981 (dashed, post-squall).



thin the anvil and subsidence beneath the anvil. The strong similarity of the vertical wind and post-squall temperature profiles to those observed in other regions suggests that this squall had a similar structure.

Rainfall

The rainfall recorded over the area traversed by the squall shows a wide variation with large falls of over 40 mm interspersed between falls of only 10 to 15 mm. In the Darwin city area (Fig. 11) the highest fall was 58.4 mm at Darwin Airport, while only 10 mm was recorded at Larrakeyah Barracks and the Botanic Gardens less than 10 km to the southwest. From the Darwin pluviograph record (see Fig. 6), it is apparent that over 80 per cent of the total fell in the first thirty minutes from the intense convective cell. The remaining 20 per cent or approximately 12 mm fell over the next five hours as progressively lighter rain from the anvil. Assuming a fairly uniform anvil rainfall of 10 to 15 mm, then the percentage of the total rainfall from this source varied from 100 per cent at the edge of the storm, to 30-40 per cent in areas of moderate rain and down to 20 per cent in the very heavy rain cores.

These results are consistent with the area-averaged anvil rainfall of 40 per cent of the total rainfall obtained by Houze (1977) for the GATE squall. The broadscale rainfall pattern then consisted of an overall 'blanket' fall of 10 to 15 mm from the anvil with embedded heavy falls of up to 60 mm from the intense convective cells on the leading edge of the system.

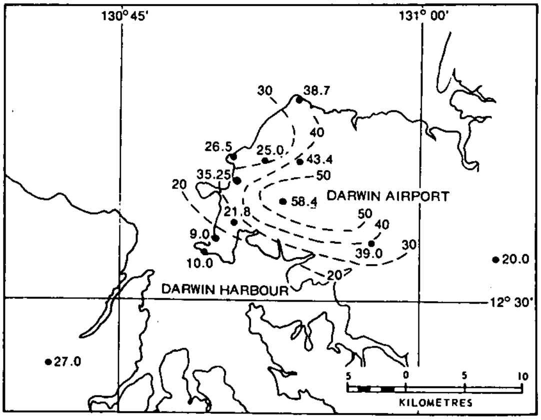
Extreme wind gusts

One of the most significant features of this squall was the extremely strong wind gusts associated with the leading edge. In mid-latitudes, the strength of these gusts can be forecast using the Fawbush-Miller technique. A similar scheme has not been developed for the tropics, so the Fawbush-Miller technique has been used operationally and found to give reasonable results in the northern Australian continental tropics.

The technique forecasts maximum wind gusts from the difference between downrush and surface temperatures. From the temperature sounding for 2200 UTC 3 January (Fig. 9), the wet-bulb temperature curve crosses the freezing level near 620 mb. Taking the saturation adiabat through this point gives a surface downrush temperature of 19 °C. Surface air temperature had remained steady at 29 °C for over four hours before the squall arrived, giving a temperature difference of 10 °C, and hence a forecast peak gust of 30 ± 5 m s^{-1}. During the passage of the squall across northern Australia it passed over four recording anemometers; two at Darwin Airport which recorded maximum gusts of 37 and 28 m s^{-1}, at Nhulunbuy (12.2 °S 136.8 °E) which recorded a maximum gust of 28 m s^{-1}, and at Centre Island (15.7 °S 136.8 °E) with a maximum gust of 25 m s^{-1}. These recordings are in general agreement with the peak gust forecast by the Fawbush-Miller technique.

The two Dines anemometers located at Darwin Airport are 1.5 km apart in a northwest — southeast line. The records from these two instruments are presented in Fig. 7. The changes in wind direction were virtually identical at both, going from west-northwest (290 °) through south to southeast (120 °) during a period of approximately five minutes.

Fig. 11 24-hour rainfall in the Darwin area to 0900 Central Standard Time 5 January 1981 (2330 UTC 4 January 1981).



However, a major difference was evident in the wind speed record at the time of squall passage. At the southeastern instrument (A) the wind became strong and gusty after the direction change to southeast had been completed. At the northwest instrument (B) the initial gust (to 37 m s^{-1}) occurred from the southwest before the wind direction change to southeast had been completed, and probably one or two minutes before the first strong gust at A.

Instrument B is located near the Darwin Airport Weather Service Office in the general aviation area where a number of parked aircraft suffered minor damage. Approximately one kilometre further west a building was unroofed and the roofing material caused damage to an adjacent electricity substation blacking out large sections of Darwin.

Fujita (1978) has defined strong, small-scale (less than 5 km) downdraughts as 'microbursts'. It is plausible that the unusual initial gust at B was caused by such an event. Studies of the detailed microscale structure of thunderstorm downdraught outflow (Charba 1974) and density currents (Simpson 1969) have shown that the strongest cold air flow occurs at hundreds of metres above the surface. This cold air 'nose' may advance more than a kilometre ahead of the surface gust front, and they suggest that 'it may periodically collapse into the warm air beneath it', thus producing sudden strong gusts or microbursts ahead of the main surface gust front.

Concluding remarks

The mesoscale structure of the northern Australian squall system of 3 to 5 January 1981 has been examined and found to be similar to that of squalls in other tropical regions. In particular, the data available are consistent with the models proposed by Zipser (1977) and Houze (1977). These describe the squall as a leading edge composed of a line of convective elements (cumulonimbus) and a larger mesoscale anvil rain area. The most significant surface feature of such a system is the leading edge. In this system it was marked by a rapid wind change (from light northwesterly to strong, gusty southeasterly) a marked temperature and dew-point fall (29 °C/24 °C down to 21 °C/20 °C) and heavy rainfall (50 mm in half an hour). The large variation in maximum wind gusts over only 1.5 km is suggestive of a microburst as defined by Fujita (1978).

The necessary and sufficient conditions for the generation of squall lines over the northern Australian tropics are still unknown. The broadscale environmental conditions over the region prior to the formation of this squall are fairly typical of the premonsoon transition season. However, three possible contributory factors can be identified; the development of the upper trough to the southwest of the Gulf of Carpentaria, leading to increased upper-level divergence (Sadler 1967) over the genesis area, the deep low over southern Queensland producing a stronger, drier south to southeast middle-level flow through the area, and a low-level southeast trade surge through central Australia leading to increased cyclonic shear vorticity and possible barotropic instability (Holton 1978). Riehl (1979) has described a similar situation, with a northeasterly surge over the North Atlantic leading to severe squally weather over Venezuela.

The combination of these three factors may have provided the necessary environment for squall line generation.

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