Evening glory wave-cloud lines in northwestern Australia

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Shortly before sunset on 10 November 1983, two spectacular low cloud lines were observed and photographed from a CSIRO research vessel about 50 km offshore, northwest of Port Hedland in Western Australia. These clouds were similar in appearance to the well-known 'morning glory' cloud lines of the Gulf of Carpentaria region. They were orientated approximately east-west and moved from the south at an estimated speed of close to 10 m s^{-1}. An analysis of available meteorological data suggests that the clouds were associated with a bore-like disturbance which was generated by the interaction of a thunderstorm gust front with the sea breeze front and which propagated on a waveguide provided by the low-level stable layer capped by a deeper adiabatic layer.

Introduction

In the last few years there has been much interest in wave and bore-like wind surges in the lower atmosphere which sometimes give rise to spectacular propagating wave-cloud lines. Perhaps the best known is the 'morning glory' phenomenon of the Gulf of Carpentaria region of northeastern Australia (Clarke et al. 1981; Smith et al. 1982; Christie and Muirhead 1983; Smith et al. 1986), but similar phenomena have been observed elsewhere, both in Australia (Robin 1978; Christie et al. 1978, 1979; Drake 1985; Mulroney 1985) and overseas (Doviak and Ge 1984; Haase and Smith 1984; Egger 1985; Eckardt and Fraedrich 1985; see also Smith et al. 1982 for additional references). Indeed, long, low cloud lines are regularly observed in high resolution satellite imagery over northwestern Australia and adjacent waters (A. Scott, C. Blackford, private communications; Clarke et al. 1981, p.1748), but the author is unaware of surface-based observations there of morning glory-type clouds, other than those to be described. Such clouds are difficult, if not impossible, to unambiguously distinguish from convective-type lines in satellite imagery alone, even in high resolution visible imagery (see e.g. Smith and Page 1985).

On 10 November 1983, two spectacular low roll clouds were observed between 2000 and 2030 WDST (Western Daylight Saving Time)† by personnel on the CSIRO research vessel *Soela* in coastal waters about 100 km northwest of Port Hedland in the north of Western Australia. A photograph of the cloud lines is shown in Fig. 1 and their successive positions as revealed by high resolution satellite imagery are shown in Fig. 2. This long-lived disturbance was still evident 18 hours after its formation. As fortune would have it, Port Hedland is the location of a Bureau of Meteorology upper air station with a daily rawinsonde flight at 2200 GMT (0700 WDST), six-hourly rawin flights, and, *inter alia,* a Dines anemograph. An analysis of surface and upper air data from Port Hedland, together with three-hourly imagery from the Japanese Geostationary Meteorological Satellite (GMS) is presented below in an effort to determine the structure and cause of the cloud line disturbance.

Data analysis

Figures 3 and 4 show segments of the daily anemograph trace and weekly barograph trace, respectively, for Port Hedland (lat. 20°22'S, long. 118°37'E) on 10 November 1983, while Fig. 5 summarises the relevant surface and upper wind data for the 36-hour period commencing 1300 on the previous day. The anemograph trace shows an abrupt change in wind direction from north-northeast to south-southeast at 1828 WDST and to within the timing accuracies of the two charts, this coincides with an abrupt pressure jump of at least 1.5 mb (note that the anemograph times are approximately 12 minutes slow while the barograph times may contain errors of at least 30 minutes). Evidently, a significant southerly disturbance replaced the sea breeze at this time.

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†Note that Western Australia had daylight saving in the summer of 1983-84. Western Daylight Saving Time = Greenwich Mean Time + 9 hours.

Fig. 1 The evening glory cloud lines of 10 November 1983 near Port Hedland, Western Australia. View is towards west-southwest, and the clouds were moving northwards. (Photograph courtesy Rolf Lindholm, CSIRO)

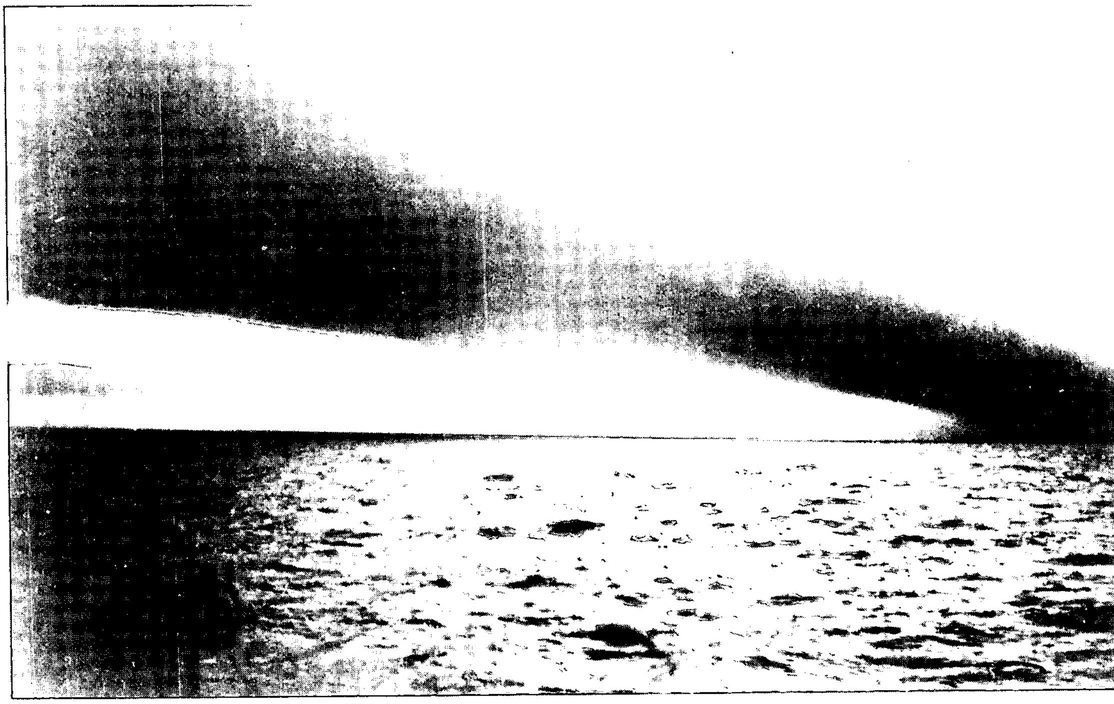
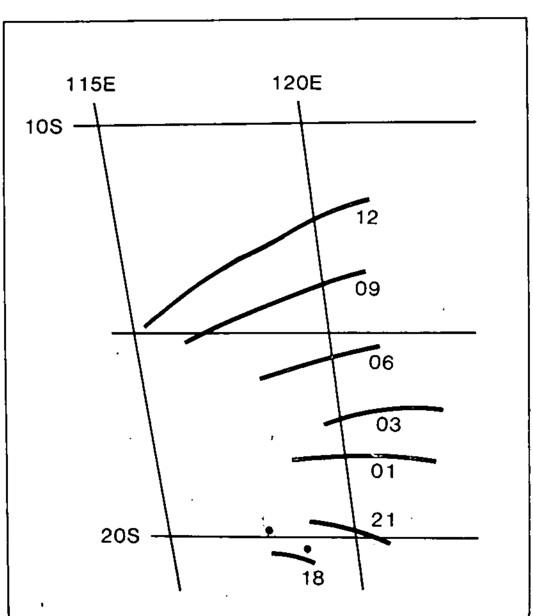


Fig. 2 Successive positions of the evening glory cloud deduced from the GMS high resolution infrared satellite imagery. Times are in WDST. The positions of Port Hedland and the CSIRO research vessel *Soela* are indicated by dots PH and SO, respectively.



At 0800, the mean sea level (MSL) isobaric chart showed an anticyclone of 1024 mb centred over the Great Australian Bight with a ridge extending northwards over much of central Australia. To the west of the ridge was a large amplitude trough with its axis along the north coast of Western Australia, the so-called 'West Australian trough'. The trough was the dominant synoptic feature in the Port Hedland region during the subsequent twelve hours. For much of the 36-hour period shown in Fig. 5, the winds up to 3 km were mostly from the continent and this is reflected in deep approximately adiabatic layers as revealed by the radiosonde data at 0700 WDST on 10 and 11 November (Fig. 6). These layers are due, presumably, to vigorous convective mixing over the land during the previous days. The stable layers below the adiabatic layer can be attributed to a combination of radiative cooling and the effect of the previous day's sea breeze (see e.g. Physick and Smith 1985).

The surface winds at Port Hedland on 10 November (Fig. 5) show clearly the development of the sea breeze, but this was replaced by a strong opposing flow, evident at 2000 WDST up to 1000 m.

The enhanced GMS infrared imagery at 1430, 1730, 2030 and 0030 WDST is shown in Fig. 7. Attention is drawn to a pair of developing thunderstorms at 1430 WDST, 100 km or so to the south and southwest of Port Hedland (Fig. 7(a)). By 1730

Fig. 3 Section of the daily anemograph trace for Port Hedland on 10 November 1983. The disturbance passage is marked by an abrupt wind reversal at 1826. (The trace times are in WDST, but are 12 minutes slow.) Wind speeds are in knots (= 0.5 m s-1).

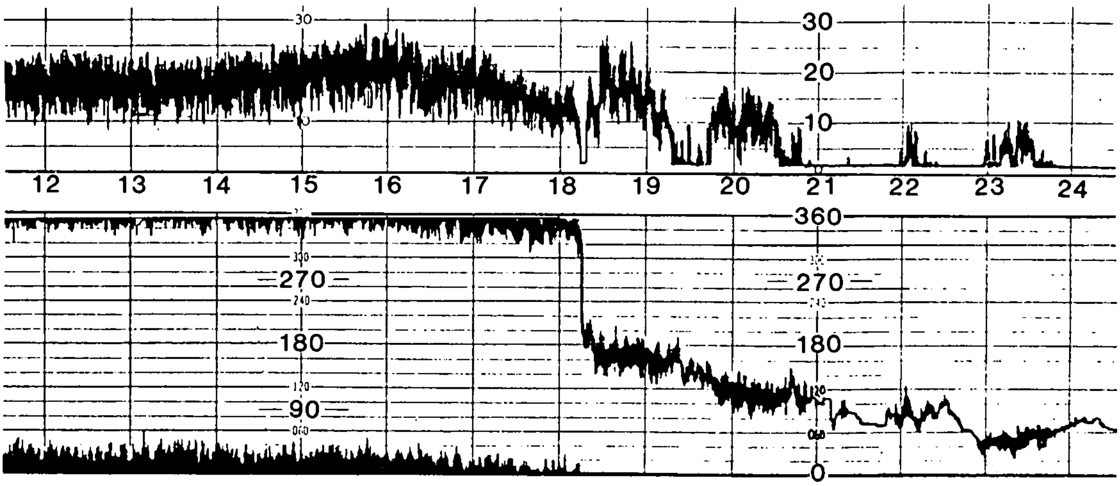


Fig. 4 Section of the weekly barograph trace for Port Hedland on 10 November 1983. The disturbance passage is associated with a sharp pressure rise marked by the arrow. Times are in WDST.

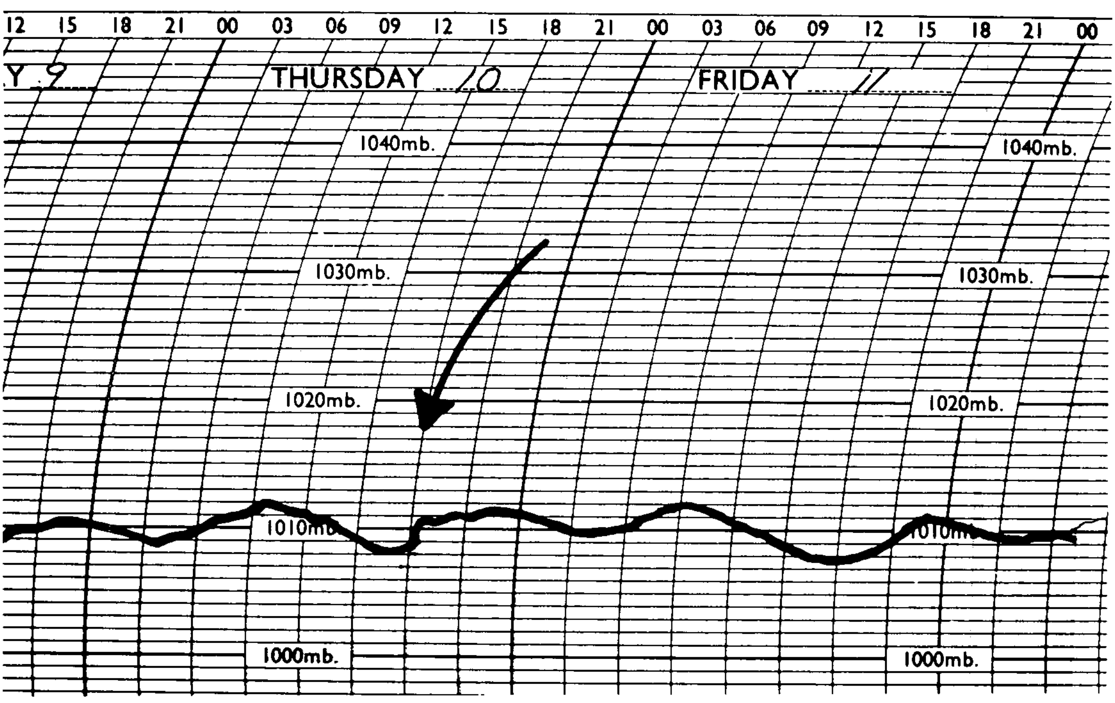


Fig. 5 **Surface and upper wind vectors at Port Hedland during the period 1300 on 9 November to 0100 on 11 November 1983. Time measures downwards. Note the scale change at 0700 on 10 November. The wind speed is proportional to the vector length, with a speed of 10 m s^{-1} equivalent to 0.4 km (marked) in the height scale.**

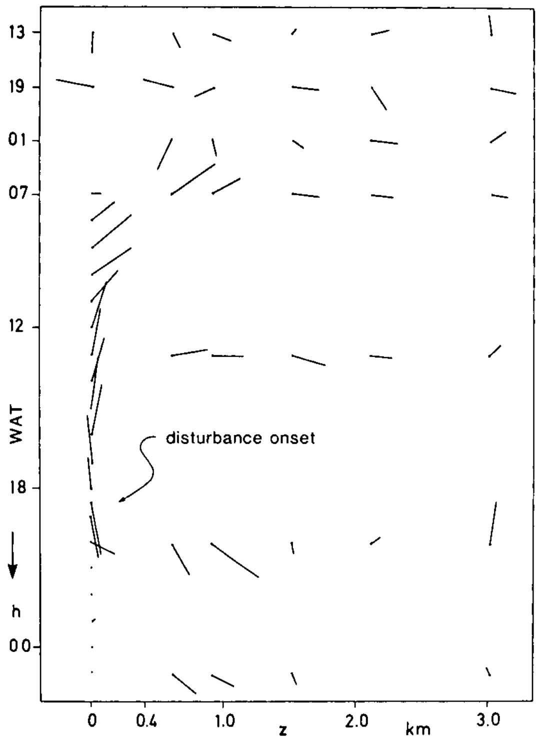
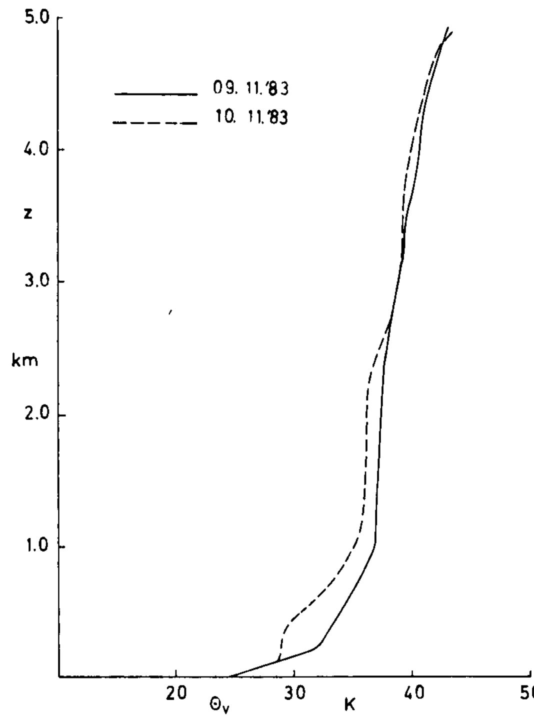


Fig. 6 **Virtual potential temperature Θ_v as a function of height based on the Port Hedland radiosonde ascents at 2200 GMT on 9 and 10 November 1983 (0700 WDST on 10 and 11 November).**



WDST, the storm tops had become merged and the storms had moved eastwards to the south of Port Hedland. It is reasonable to suppose that the southerly change and pressure jump at Port Hedland just before 1830 WDST was a manifestation of the gust front from these storms, although the 'evening glory' clouds cannot be detected in Fig. 7(b) at Port Hedland. The southerly surge itself persisted for about an hour, after which the surface wind backed to the southeast then east (Fig. 3). At 2030 WDST, the storms had moved to the east of Port Hedland and by this time there was a well-defined line of low cloud trailing to the north and west of them; this is marked by an arrow in Fig. 7(c). It seems likely that this line marks the surface gust front, or the wave disturbance into which it has evolved. Four hours later, the line has grown to over 500 km in length in the form of an arc (ABC in Fig. 7(d)), the western portion AB being orientated approximately east-west. Subsequently, it can be followed in successive three-hourly imagery as it moves northwards and is still recognisable at 1430 WDST on 11 November some 20 hours after the disturbance passed over Port Hedland. At the longitude of Port Hedland, the line maintains a uniform speed normal to itself to 9.7 m s^{-1} between successive satellite photographs until 0600 WDST on 11 November, increasing to between 12.5 and 13 m s^{-1} thereafter. This is similar to the propagation speed of northeasterly morning glory surges over the Gulf of Carpentaria (see e.g. Clarke et al. 1981, Fig. 17; Clarke 1983, Table 4).

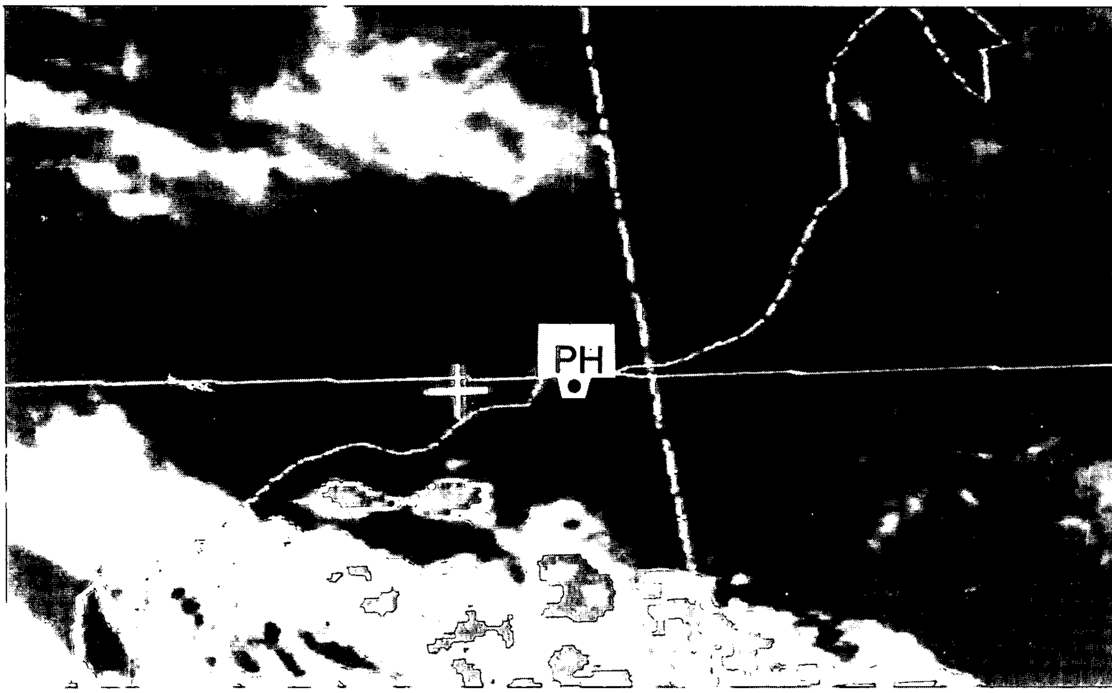
The two cloud lines in Fig. 1 were photographed at about 2015 (± 10 minutes) at a location near lat. 19°50'S, long. 117°45'E. Assuming that the cloud lines were orientated exactly east-west, the speed of northward movement between Port Hedland and the CSIRO vessel is estimated to lie between 8.7 m s^{-1} and 10.1 m s^{-1}, in broad agreement with the satellite-derived speed.

Discussion and conclusions

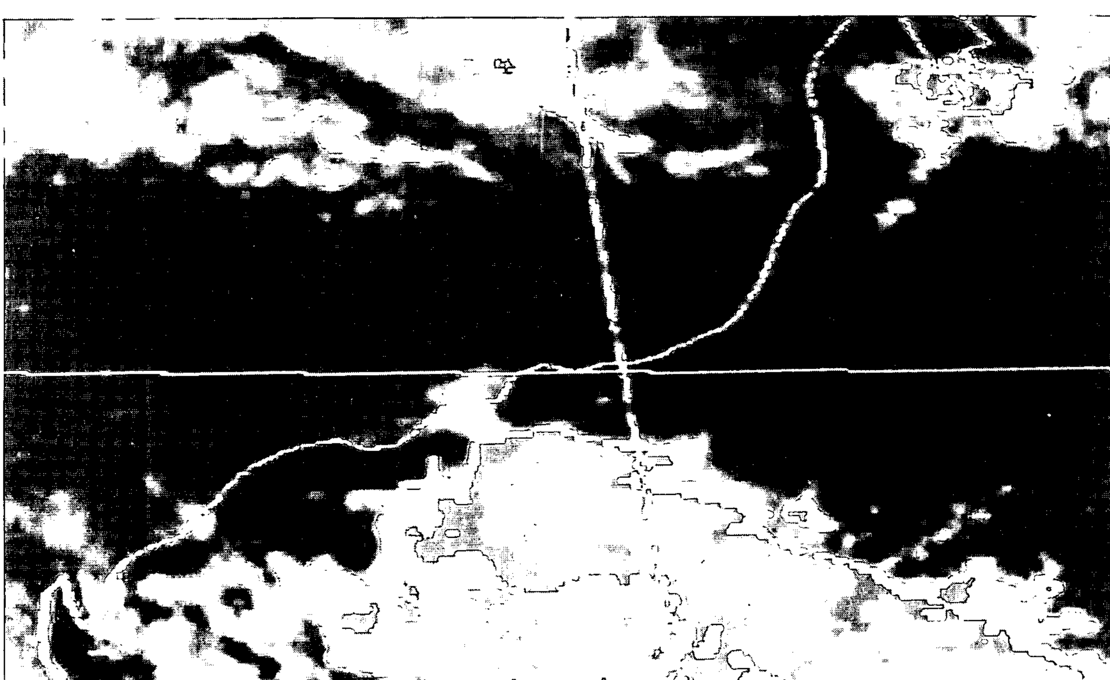
On the evidence of the available data it seems likely that the evening glory cloud lines shown in Fig. 1 were initiated by the cold air outflow from the two thunderstorms to the south, evident in Fig. 7(a). A

Fig. 7 Portions of the enhanced Japanese Geostationary Meteorological Satellite imagery for (a) 1430 WDST, (b) 1730 WDST, (c) 2030 WDST, and (d) for 0300 WDST on 11 November 1983. Note the two developing thunderstorms marked by arrows just south and southwest of Port Hedland (at the point PH) in (a); the trailing cloud line (arrowed) in (c); and the arc cloud line ABC in (d).

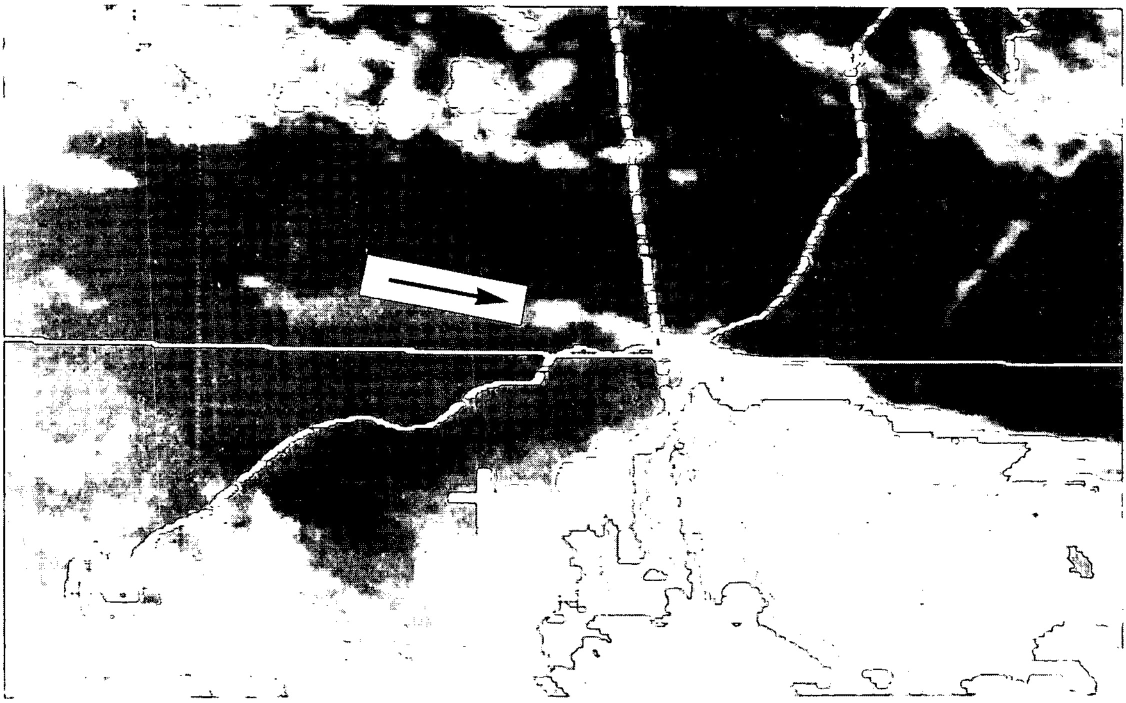
(a)



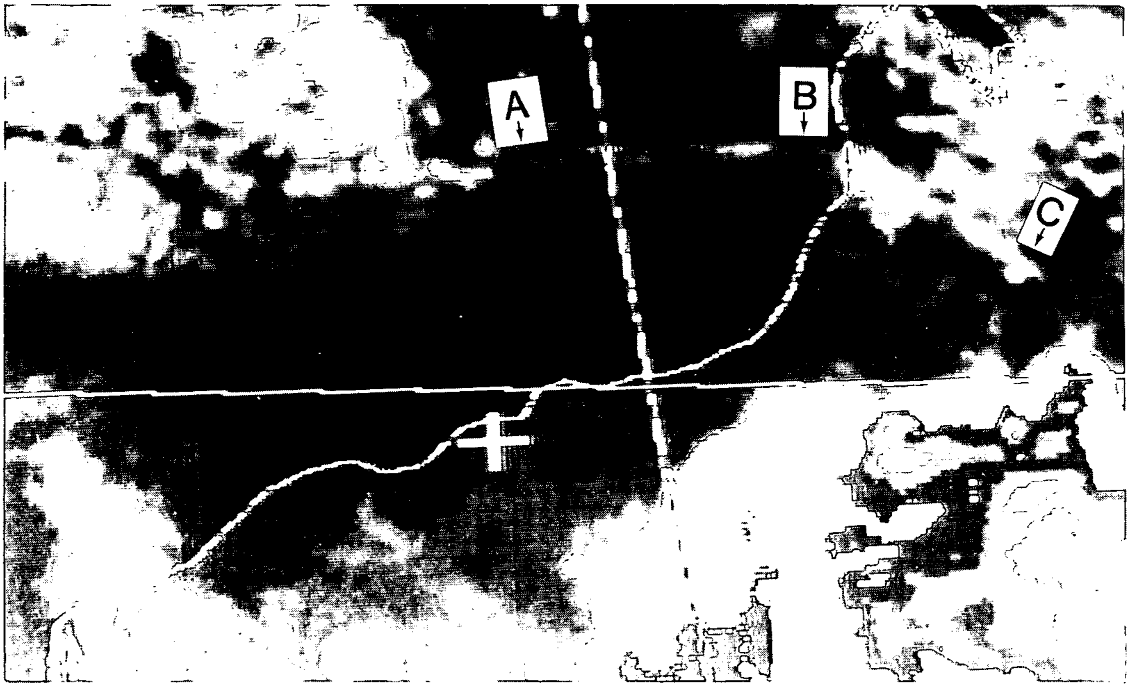
(b)



(c)



(d)



probable scenario is as follows. As the sea breeze front moved inland during the afternoon, it encountered the northward moving gust front marking the leading edge of the cold air outflow from the two storms. The collision of the gust front with the sea breeze front would provide an effective means of initiating a line disturbance, in much the same way as the collision of the east and west coast sea breezes over Cape York Peninsula is believed to initiate the morning glory (Clarke 1985; Noonan and Smith

1986). The evolution of the disturbance as a series of solitary-type waves, in this case marked by the two cloud lines, could be expected, in the same way that the morning glory disturbance evolves (see e.g. Smith and Morton 1984). The northward motion of the disturbance was due presumably to the greater intensity of the gust front as compared with the sea breeze. The configuration of static stability exemplified by the potential temperature soundings at Port Hedland (Fig. 6) provides an effective waveguide for the propagation of trapped internal gravity waves. The surface-based stable layer over the sea would be expected to result from an adjustment of the warmer continental air aloft to the cooler sea surface. During the day the stable layer is advected inland with the sea breeze. The nearly adiabatic layer aloft is a consequence of convective mixing of the air while it lay over the continent and plays a central role in suppressing the vertical radiation of wave energy, effectively trapping the disturbance.

Other examples of propagating wave-type disturbances in the lower atmosphere thought to have been generated by thunderstorms have been documented by Schreffler and Binkowski (1981), Doviak and Ge (1984) and Haase and Smith (1984). In all these examples, the evidence points directly to the generation of a wave disturbance by a single gravity current (associated with the thunderstorm gust front, or the merged gust front of a storm complex) interacting with a wave-guide such as described above. This type of interaction has been studied experimentally by Maxworthy (1980) and Smith et al. (1982), and in numerical simulations by Crook and Miller (1985) and Haase (1985, private communication). A new element in the present case study is the role of a second gravity current, the sea breeze, both in providing the stable layer over the land suitable for wave propagation and as an obstacle to the gust front to ensure a significant initial disturbance.

Acknowledgments

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