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The Morning Glory: an extraordinary atmospheric undular bore

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SUMMARY

Observations made during an expedition in October 1980 to study 'morning glory' wind squalls in the Gulf of Carpentaria region of northern Australia are described. During a ten day period in Burketown, north Queensland, six squalls were documented on consecutive mornings (8–13 October), including two moving from the south, an apparently unusual direction. The unique data gathered from the latter confirm that these have the same character as their north-easterly counterparts; that is, they are undular bores. The origin of southerly glories remains uncertain, but, at least, in some cases, appears to be linked with the northeast advance of a frontal trough across central Australia. While the data are equivocal, it seems possible that the motion of the front into the developing nocturnal inversion could generate waves, or hydraulic-type disturbances, which run along the inversion layer, ahead of the front, as proposed by Tepper (1950). The efficacy of such a mechanism is demonstrated by a simple laboratory experiment.

Evidence is presented which suggests that morning glory type events occur elsewhere in the world, sometimes as precursors to cold fronts. Observations in the Gulf of Carpentaria region show that they are effective triggers of deep convection when they advance into air with a sufficient degree of conditional instability.

1. INTRODUCTION

Morning Glory is the name given to a type of wind squall, or succession of wind squalls, which occurs early in the morning, mainly in the late dry season (mid-August to mid-November), at places around the southern coast of the Gulf of Carpentaria in northern Australia (see Fig. 1). The name derives from a spectacular roll cloud, or series of roll clouds, frequently accompanying the more intense squalls. A further characteristic is the sharp surface pressure rise associated with the passage of each squall, the leading rise sometimes exceeding one millibar in a few minutes. Until recently, it was thought that the morning glory invariably travelled from the sector between north and east, but little was known about its structure and origin (Neal *et al.* 1977).

In late 1979, an expedition to the Gulf region organized by R. H. Clarke and the first author collected aerological and surface data on two morning glories, revealing the phenomenon as an undular bore propagating on the stable, low level maritime or nocturnal inversion (Clarke *et al.* 1981; Smith and Goodfield 1981). Its origin appears to lie frequently in the interaction of a deeply penetrating sea breeze front with the developing nocturnal inversion over Cape York Peninsula, but there is evidence that, on occasion, the katabatic flow on the western slopes of the Peninsula may also play a role.

On 6 October 1979, just as the main expedition group was preparing to leave its centre of operations at Burketown, north Queensland, a southerly moving morning glory was observed. The squall was preceded in the Burketown area by dense fog which was swept away with the passage of the leading squall. The receding fog bank had a remarkably straight edge (Fig. 2) and was followed by a parallel roll cloud and associated wind squall, an estimated ten kilometres behind. The direction of propagation of this disturbance was a surprise and clearly pointed to a different source region (and possibly generation mechanism) to the more usual morning glories from the northeast. In view of this, its time of occurrence at Burketown at 0700 (all times refer to Local Standard Time) was equally surprising, being about the time of maximum frequency of occurrence there of disturbances from the north-east. Unfortunately, at the time of passage, our equipment had been dismantled and the

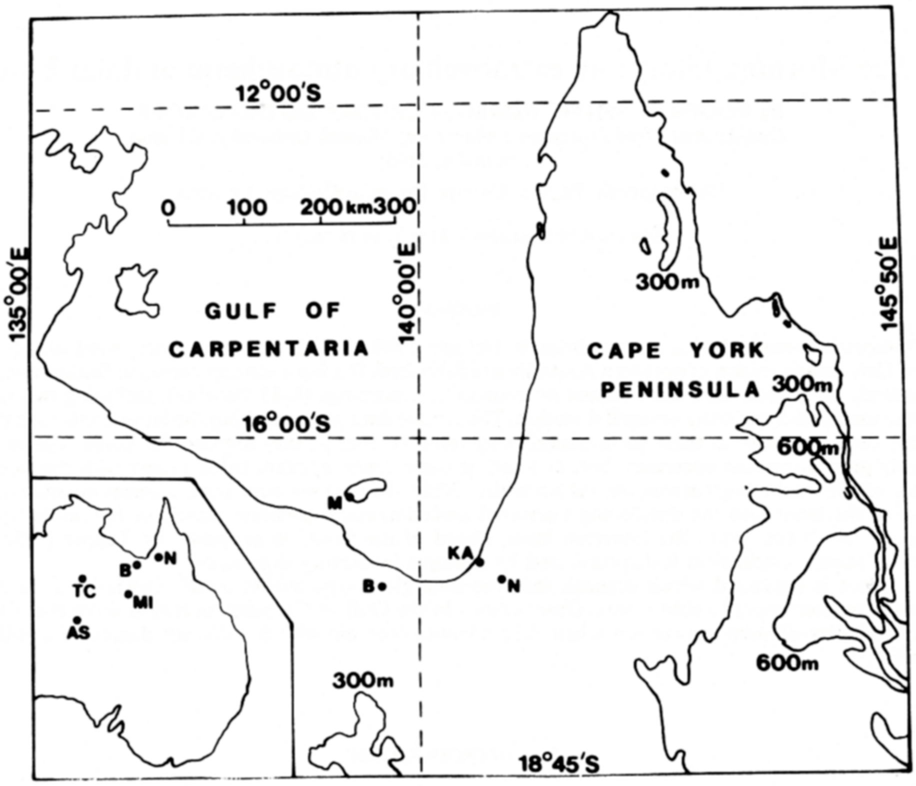


Figure 1. Map of northeastern Australia, showing locations mentioned in the text, with topographic contours. Abbreviations are: AS Alice Springs; B Burketown; KA Karumba; M Mornington Island; MI Mount Isa; N Normanton, TC Tennant Creek.

Figure 2. Receding fog bank associated with the southerly morning glory of 6 October 1979 at Burketown, looking northwest.

main data available on this event are those from the Bureau of Meteorology's operational surface network, together with a small network of stations clustered around Mount Isa and operated by Mount Isa Mines Ltd. These data were supplemented by excellent satellite imagery from the United States Defense Meteorological Satellite (DMS). The circumstances leading to this event have been pieced together by Christie *et al.* (1981).

In 1980, the three authors and their colleague T. Long returned to the Gulf for a two week period in an effort to document additional morning glories. Our objective was to determine low level winds (up to a height of about 2 km), prior to and following the passage of morning glories, by tracking helium-filled pilot balloons (pibals). It was sought also to obtain detailed pressure traces during glory passages using a sensitive digital aneroid barometer, and to obtain photographs of glory clouds. A Woelfle anemograph was used to record surface wind speed and direction continuously for the period. During this brief and modest expedition, an unprecedented number of events were recorded. Over ten mornings of operations in Burketown, six glories occurred on consecutive mornings (8–13 October) including two from a southerly direction. Morning glories occurred also on two of the following three days (15, 16 October) while the group was stationed in Karumba, 200 km east of Burketown.

We present herein an analysis of the observations at Burketown, with particular emphasis on the unique data set obtained for the disturbances moving from the south. The latter are shown to be similar in structure to their north-easterly counterparts, despite their different origin. A brief review of apparently related pheomena elsewhere in Australia and overseas is presented also. Finally, some speculations on the generation mechanism(s) are illustrated by a simple laboratory experiment.

2. Observations

The observations of morning glories from the northeast sector collected during the 1980 expedition represent a significant increase to the total data set on such events and add support to the conclusions of Clarke *et al.* (1981) with regard to the structure of these disturbances. However, the data for the two southerly morning glories which occurred on 9 October and 12 October 1980 (henceforth 9 October is referred to as the 9th, etc.) are unique and we concentrate herein on an analysis of these. Nevertheless, a brief description of the other four events is given as it serves to highlight the seemingly unique situation of the Gulf of Carpentaria region vis-à-vis the high frequency of morning glory occurrences there, as well as the astonishing range of manifestations of this phenomenon. The six events are described in chronological order.

8 October 1980 The morning glory on this day was unaccompanied by cloud at Burketown and was only recognized as such some hours later by the small pressure jump (less than 0·8 mb) it produced in the daily barograph trace at 0600, and the characteristic wind speed and direction signature recorded on the anemograph. The trace from the latter is shown in Fig. 3. Note the times on the Woelfle trace are twenty minutes slow. Prior to the glory passage, from about 0420, surface winds were southwesterly with a steady mean speed of about 3 m s^{-1}. With the passage of the glory, the wind swung abruptly to east-northeasterly and the speed increased to 4·0 m s^{-1}. After about ten minutes it reverted briefly to southwesterly, then to easterly, about which it oscillated, before returning to southwesterly at about 0635. Subsequently, it remained steady from this direction until about 0730 when a further abrupt change heralded winds with a substantial easterly component. These were to persist, becoming more northerly as the day progressed on account of the usually well developed sea breeze.

What is presumably the same event produced larger pressure jumps, both about 1·2 mb, at Normanton at 0206 and Mornington Island at 0554. On the assumption that the pressure

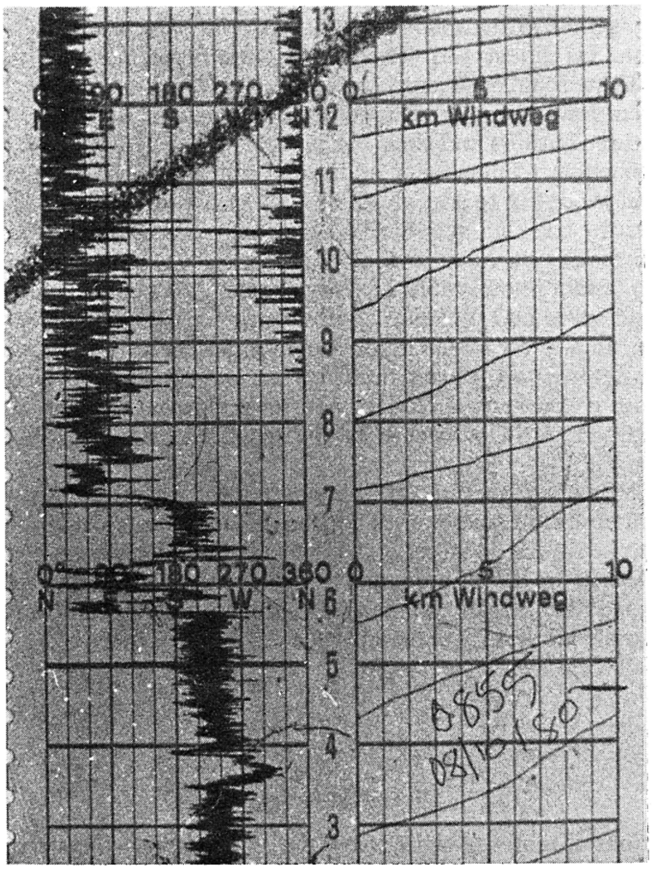


Figure 3. Anemograph trace on the morning of 8 October 1980 at Burketown. Times on the trace are twenty minutes slow.

jump line was straight (see Clarke *et al.* 1981, p. 1733), its average velocity is estimated to be $11{\cdot}0\,\mathrm{m\,s^{-1}}$ from the direction 67°, typical of morning glories from the northeast (see Clarke *et al.* Fig. 17).

The pibal wind data were obtained close to the times of large surface wind reversals making interpretations of these difficult.

9 October 1980 The surface winds for half an hour prior to this event were light, averaging $0{\cdot}5\,\mathrm{m\,s^{-1}}$, from the sector west to west-northwest. Just before 0615, the first of several parallel lines of discrete wave-like clouds was observed in the south and the first pibal ascent was commenced. Unfortunately, the leading wind squall was unaccompanied by cloud and arrived without warning at 0622, just before pressure readings were commenced. However, a pressure jump of about 0·6 mb was recorded on the barograph trace at the same time as the squall. The first cloud line (Fig. 4) passed over Burketown about 0638, accompanied by a second wind squall. It was estimated that the cloud lines moved from a direction of about 165°. At Mornington Island, a pressure jump of about 1·0 mb was recorded at 0835. Hence, assuming that the pressure jump line is straight and oriented along the cloud line, the times of passage at Burketown and Mornington Island give an average speed for the glory between these locations of $15\,\mathrm{m\,s^{-1}}$ (since the disturbance was moving almost along the

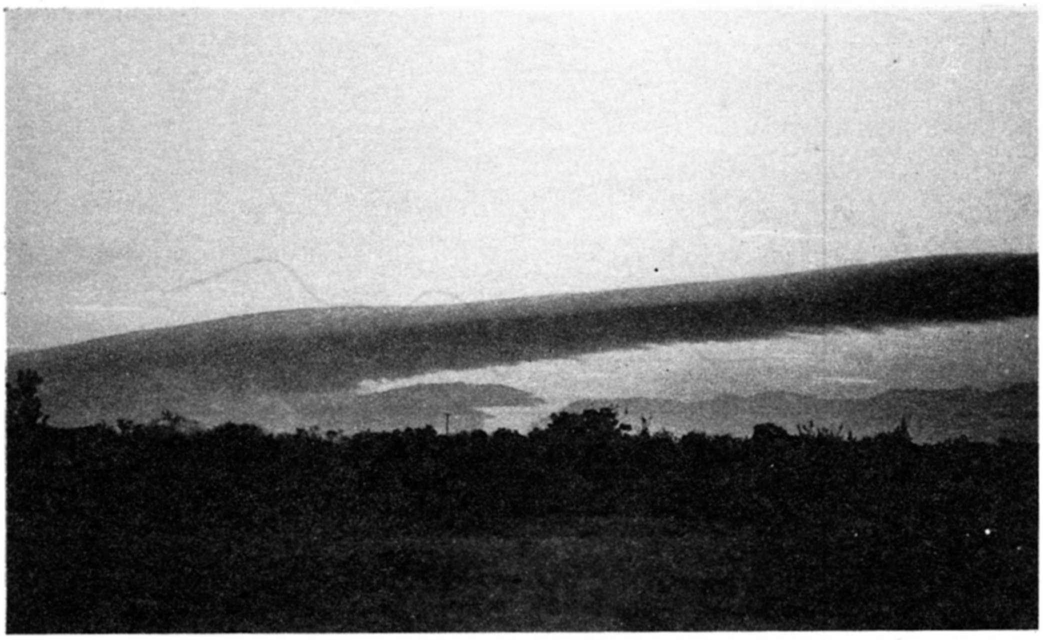


Figure 4. Leading cloud line of the southerly morning glory of 9 October 1980 at Burketown, looking southeast.

direction from Burketown to Mornington Island, this estimate may be regarded as an upper bound for the propagation speed).

The variation of surface wind speed and direction determined from the anemograph trace is shown in Fig. 5, together with that of surface pressure obtained from the digital aneroid barometer, adjusted for the diurnal variation (henceforth, such wind and pressure data are referred to as the surface data). The adjusted pressure was obtained by subtracting the mean diurnal pressure variation for the time of year based on five years of data from Mornington Island, the closest station in both latitude and longitude to Burketown where records are available. These diurnal variations were kindly provided by our colleague, R. H. Clarke. Following the initial pressure rise, most of which appears to have occurred before readings were commenced, the pressure oscillates for a period of about an hour, the mean adjusted pressure rising by over a millibar during this time. The wind speed and direction oscillates also, with a period of about 13 minutes. The maximum wind gusts blow from a direction a little east of south, close to the estimated direction of motion of the cloud lines. Note that the wind speed and direction are in phase, at least for the leading two waves. The pressure maximum lags the wind speed by about five minutes, although the latter coincides closely with the maximum pressure gradient. Note that there are inaccuracies of one to two minutes in the timing of wind gusts determined from the anemograph trace.

As noted earlier, no balloon winds were obtained before the passage of the disturbance, but double theodolite ascents were made at 0615, 0703 and 0720. The wind components in the direction of motion of the cloud line and at 90° to its right, are shown in Fig. 6 as functions of height. Note that with the exception of the 0615 sounding, the wind has a component in the direction of propagation at all heights up to 600 m, the maximum speeds in this direction being of order 8 $m s^{-1}$ at heights of about 200–250 m. However, these speeds are much less than the propagation speed and, as in the case of morning glories from the northeast, the low level relative winds are away from the pressure jump line. The phenomenon is therefore not a gravity current. Indeed, the data are entirely consistent with the

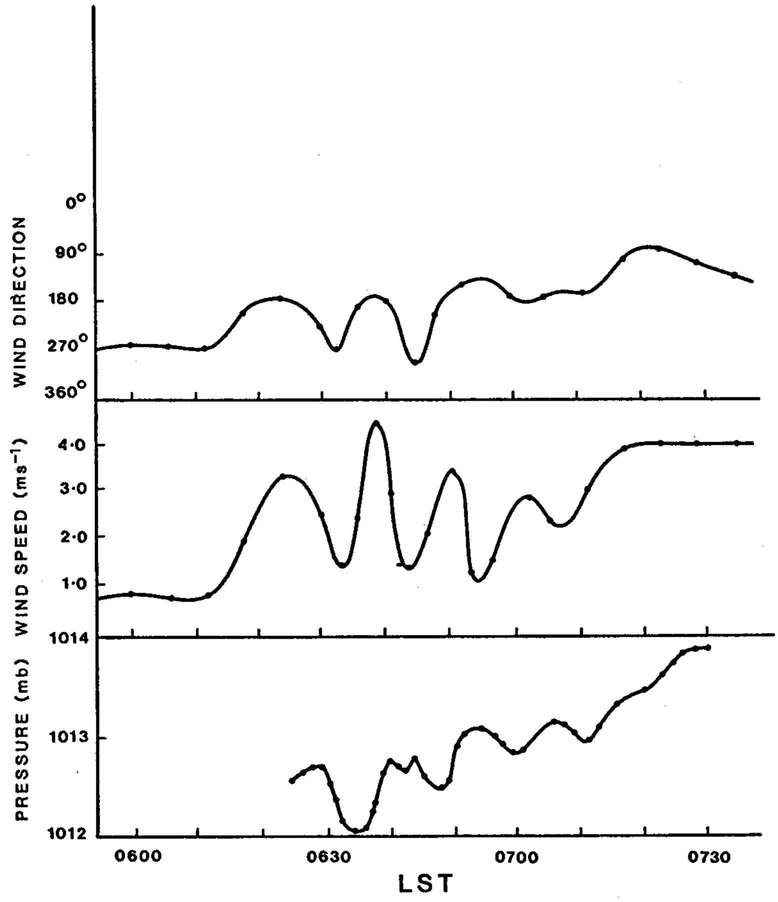


Figure 5. Surface wind speed and direction derived from the anemograph trace and surface pressure obtained from a digital aneroid barometer for the morning glory of 9 October 1980 at Burketown. Such data is referred to in the text as *the surface data.*

interpretation of this disturbance as an undular bore, with similar structure to morning glories from the northeast. Figure 6 shows that the transverse wind component has significant variation with height, with a strong low level flow to the right of the direction of propagation below 600 m. Moreover, the component has a similar vertical structure in all three ascents.

When the wave system moved out over the Gulf, large cumulus congestus clouds were observed to form (Fig. 7). This is evidence that the vertical displacements in the disturbance were sufficient to trigger the release of conditional instability in the moister air over the sea.

10 October 1980 Throughout most of the night, the surface wind was steady and westerly with a speed of about 2·0 m s^{-1}. At about 0440 it backed south-westerly, falling in strength to 1·6 m s^{-1} and then to almost calm (< 0·6 m s^{-1}) at 0535. The surface data from 0530 is shown in Fig. 8. The pressure trace on this day is incomplete being composited from two partial records made at locations 14·5 km apart, approximately in the direction of motion, but a pressure jump was recorded on the barograph trace at about 0605. Larger pressure jumps were recorded at three other locations: 1·2 mb at 0210 at Normanton; 1·0 mb at 0240 at Karumba; and 0·8 mb at 0635 at Mornington Island. With the usual assumptions,

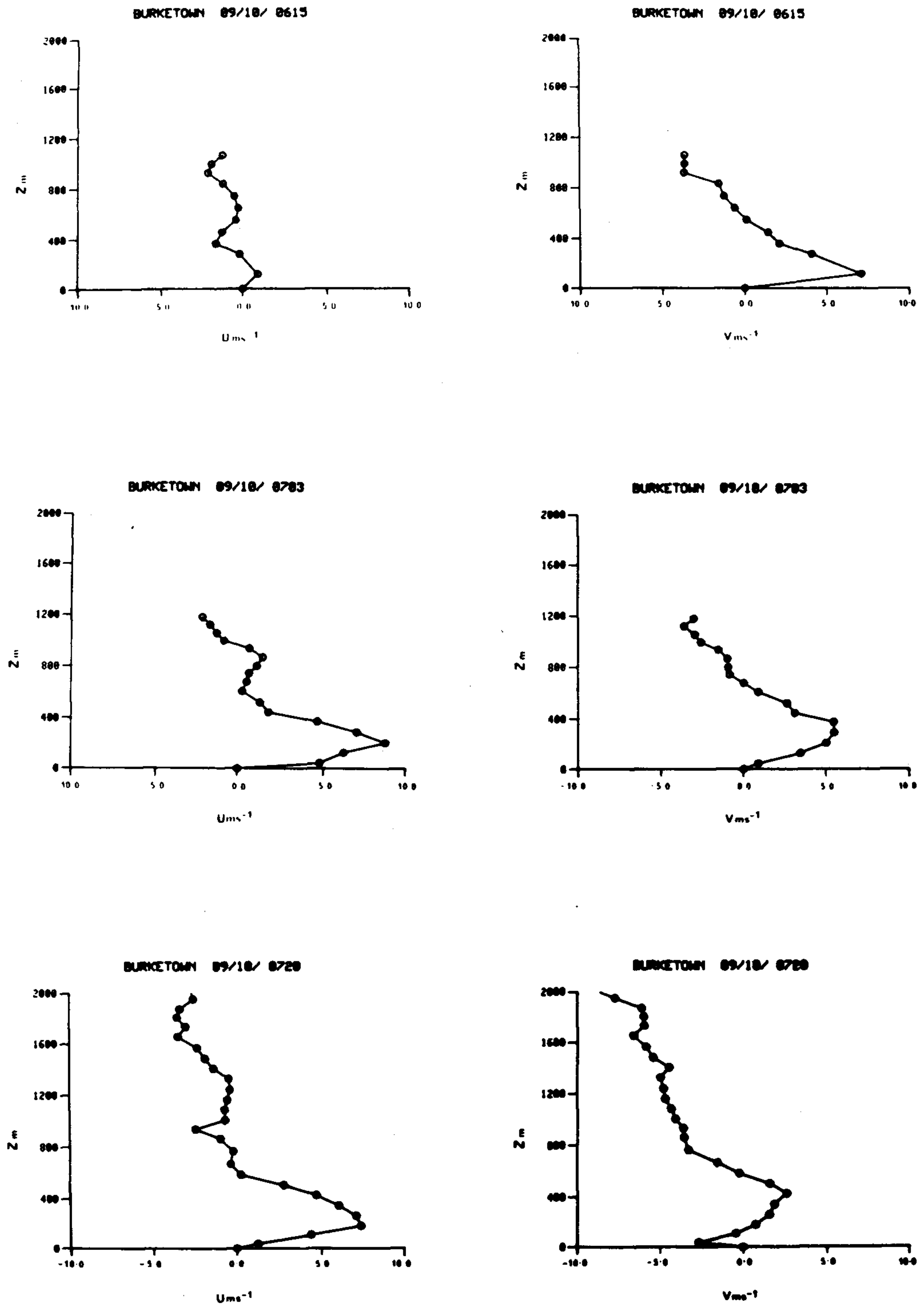


Figure 6. Profiles with height of low level wind components, u in the direction of glory motion and v in the direction transverse and to the right of it for the event of 9 October 1980.

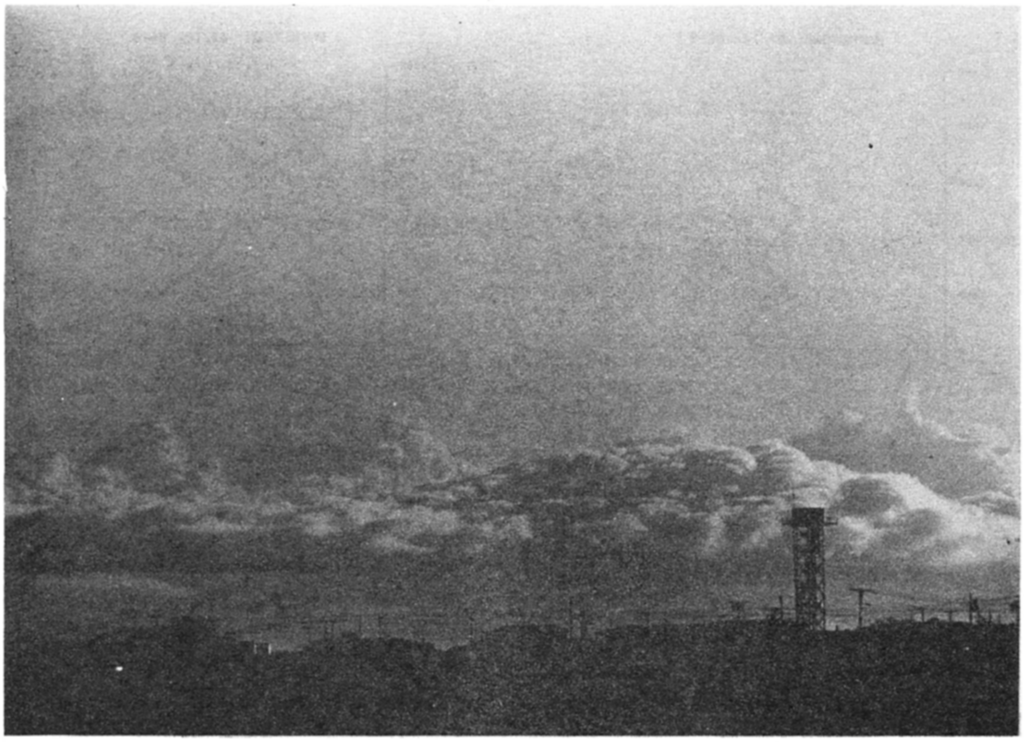


Figure 7. Cumulus clouds over the Gulf of Carpentaria apparently generated by the movement out to sea of the southerly morning glory of 9 October 1980. View is from Burketown looking north.

these times of passage give an average velocity for the disturbance of $10{\cdot}5\,\mathrm{m\,s^{-1}}$ from 70°.

At 0556, a sharp wind change occurred, the speed increasing to $2{\cdot}0\,\mathrm{m\,s^{-1}}$ from the north-northeast. This was followed by a sharper wind squall at 0623, accompanied by the passage overhead of a well developed cloud line (Fig. 9), stretching from horizon to horizon, with an estimated orientation of 155°/335°, within 5° of the orientation of the pressure jump line as determined above. The passage of the glory was accompanied by a regular series of pressure oscillations with the mean adjusted pressure increasing by 2·0 mb between 0530 and 0700.

Pibal ascents were made at 0527, 0605 and 0648. Preceding the glory at around 0530, the wind was westerly to a height of about 400 m, then veered sharply, becoming north-easterly about 700 m. A similar structure was evident in the sounding at 0605, close to the time of the initial pressure jump. Following the passage, however, the wind below 400 m had changed to northeasterly, an almost complete reversal of the low level flow, whereas the winds above this level remained similar to the pre-glory distribution, with a shallow layer of northwesterlies above 500 m veering to north-northeasterlies above 900 m, thence to north-easterly above 1500 m.

11 October 1980 Between 0610 and 0620, a relatively weak disturbance, accompanied by two rather diffuse cloud lines, passed over the observing station. During this period, the surface wind changed from a light northwesterly, averaging $0{\cdot}6\,\mathrm{m\,s^{-1}}$, to a northeasterly of $2{\cdot}5\,\mathrm{m\,s^{-1}}$. Over the next hour, it steadily increased in strength to $6{\cdot}0\,\mathrm{m\,s^{-1}}$ and backed northerly, remaining in this state for many hours. The adjusted surface pressure (not shown) rose steadily by 0·4 m b between 0615 and 0715, but there was no sign of any oscillation or discontinuity.

Pressure jumps at 0329 at Karumba and at 0530 at Mornington Island were recorded on

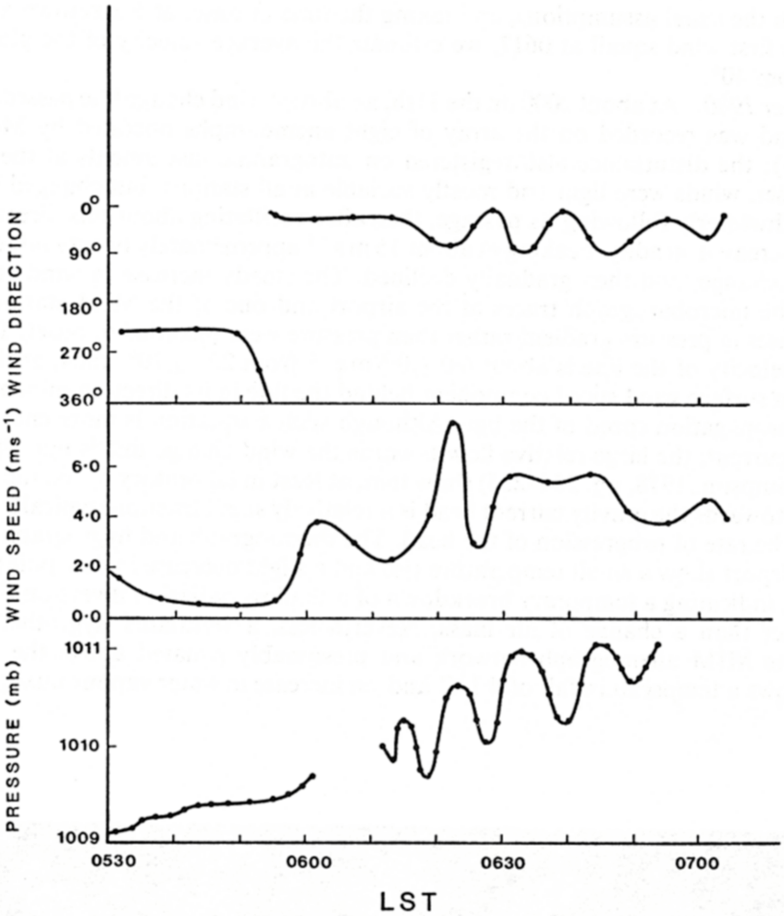


Figure 8. Surface data for 10 October 1980.

Figure 9. Morning glory of 10 October 1980 looking north-northeast from Burketown.

this day. With the usual assumptions, and taking the time of onset at Burketown as coincident with the first wind squall at 0617, we estimate the average velocity of the glory to be $11{\cdot}5\,\mathrm{m\,s^{-1}}$ from 40°.

12 October 1980 At about 2000 on the 11th, an abrupt wind change line passed through Mount Isa and was recorded on the array of eight anemographs operated by Mount Isa Mines (MIM); the disturbance also registered on autographic instruments at the airport. Before its onset, winds were light and mostly variable at all stations, but changed abruptly to south-southwesterly following its passage, thereafter oscillating about this direction. The wind speed increased steadily, peaking at about $15\,\mathrm{m\,s^{-1}}$ approximately twenty minutes after the direction change, and then gradually declined. The steady increase in wind speed was reflected in the microbarograph traces at the airport and one of the MIM stations where abrupt increases in pressure gradient rather than pressure were recorded at onset. The array determined velocity of the line is about $6{\cdot}0 \pm 0{\cdot}5\,\mathrm{m\,s^{-1}}$ from $225 \pm 10°$; thus, at this stage, the maximum surface wind speed component behind the line in its direction of propagation exceeds the propagation speed of the line. Although such a situation is more characteristic of a gravity current, the large relative flow towards the wind change line is not. Studies by Britter and Simpson (1978, pp. 234–235) show that, at least in laboratory flows, the low level 'feeder' flow towards the gravity current head is a relatively small fraction, typically less than one half, of the rate of progression of the head. The thermograph and hygrograph traces at Mount Isa airport show a small temperature rise and a slight decrease in dew point, both of about 1–2 K, indicating a temporary breakdown of a shallow radiation inversion by vertical mixing, rather than a change of air mass. Nevertheless, a ventilated hygrothermograph located in the MIM anemograph network and presumably situated above the radiation inversion shows a temperature fall of 4·1°C and an increase in water vapour mixing ratio of

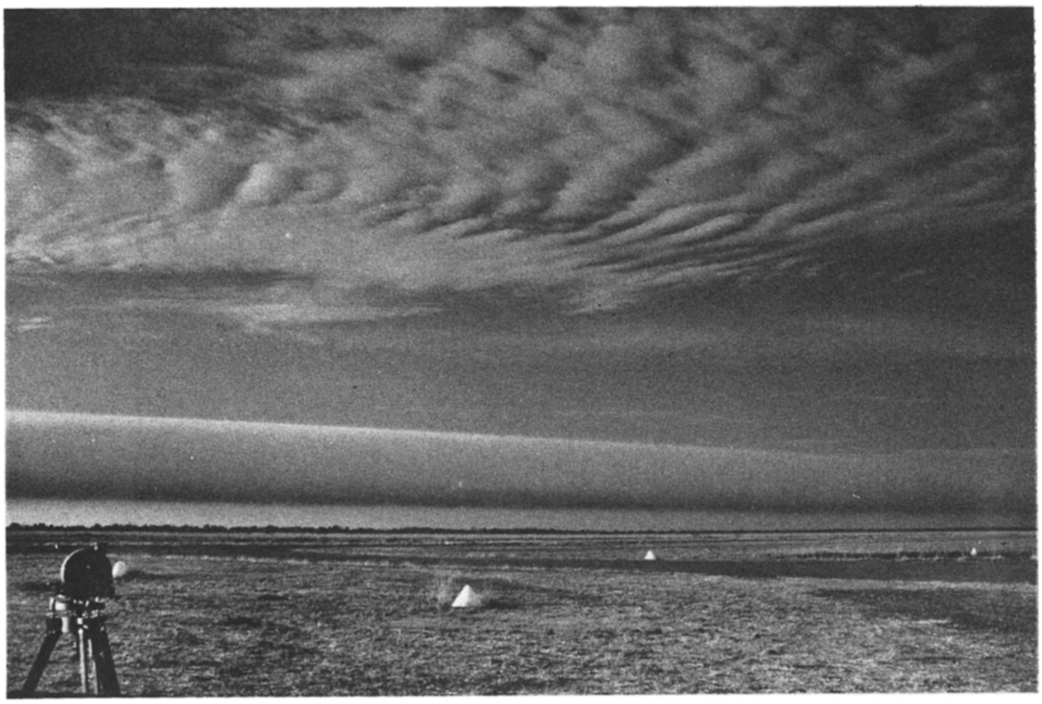


Figure 10. Southerly morning glory of 12 October 1980 looking south-southwest from Burketown.

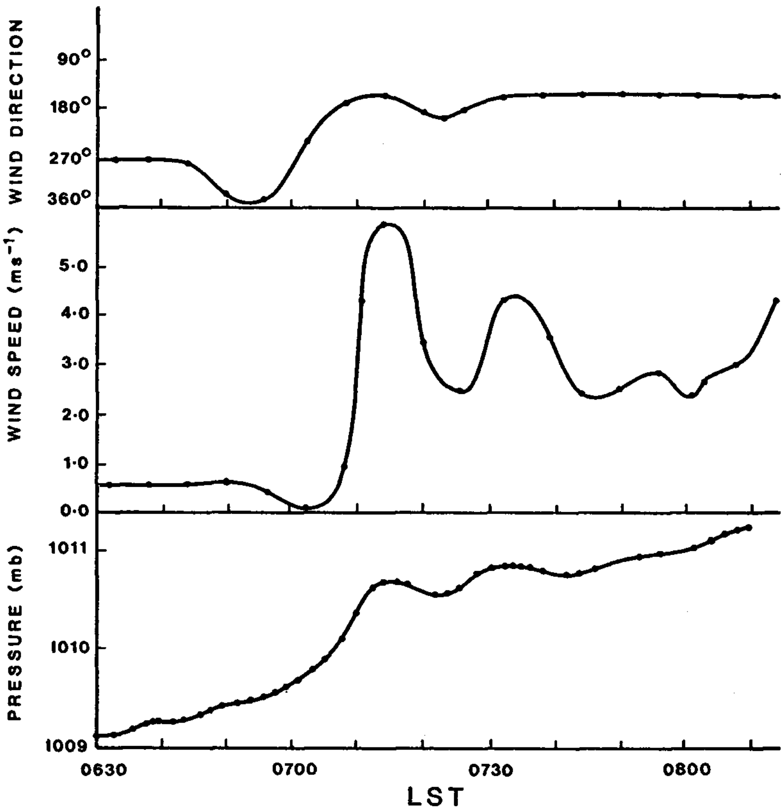


Figure 11. Surface data for 12 October 1980.

0·6 g kg^{-1} between 1930 and 2030, the sharpest temperature fall being about 2·5 °C in five minutes just before 2000.

Although there are no data between the Mount Isa locality and Burketown, it seems reasonable to suppose that the foregoing disturbance at Mount Isa is related to the spectacular morning glory observed at Burketown on the 12th. This was accompanied by two long, large amplitude, parallel wave-clouds, oriented approximately along 80°/260° and moving from 170°. The first of these, shown in Fig. 10, passed over the observation station at 0714.

The surface data for this event are shown in Fig. 11. As on the 11th, the surface winds prior to passage were light, less than 0·6 m s^{-1}, from the northwest. With the passage, the velocity changed abruptly to 6·0 m s^{-1} from the south, thereafter moderating in strength with little change in direction. The surface pressure rose sharply by over a millibar and continued to rise slowly, even when adjusted to remove the diurnal variation.

Double theodolite pibal ascents were performed at 0532, 0633, 0709 and 0749. The low level wind components normal to and parallel with the cloud line prior to (at 0633) and after (at 0749) its passage are shown in Fig. 12. As on the 9th, it can be seen that before passage, the low level winds are in the opposite direction to the motion of the disturbance, whereas, behind the disturbance, the low level winds have a component in the direction of propagation.

At 0907 a pressure jump of 0·3 mb occurred at Mornington Island. Assuming the glory continued to move from 170°, its average speed between Burketown and Mornington Island

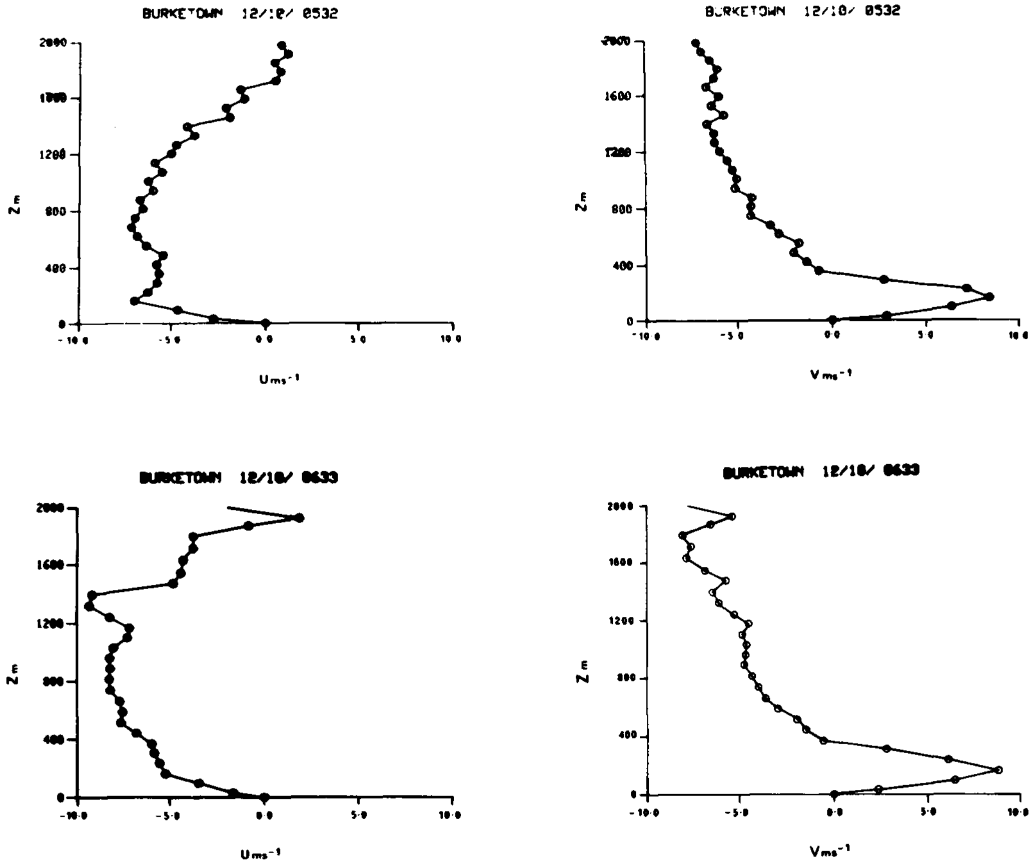


Figure 12. Legend as for Fig. 6. except for 12 October 1980.

is estimated, for the same reasons as on the 9th, to be as high as $17\,\mathrm{m\,s^{-1}}$. Once again, this significantly exceeds the wind component in the direction of motion at all levels behind the disturbance, the maximum values for which are about $4\,\mathrm{m\,s^{-1}}$ (Fig. 14). Therefore, as the adjusted surface pressure increase is maintained well behind the disturbance, we are led to interpret this event at Burketown as an undular bore. Evidently, a considerable degree of evolution in structure occurred during the night as the disturbance moved northwards from Mount Isa.

13 October 1981 The morning glory on this day was the most intense, as far as cloud size and pressure jump are concerned, of the six disturbances. This event, which arrived from the northeast at the relatively early time of 0545 at Burketown, was accompanied by three very impressive large amplitude roll clouds with some less developed cloud lines behind. In the direction from which it came was a large cumulus cloud mass, presumably including cumulonimbus also as several lightning flashes were observed in the distance in that direction. A photograph taken west of Burketown at about 0600 looking along the first cloud line is shown in Fig. 13. Note the inclination of trees caused by the strong wind gust accompanying the cloud.

The surface data are shown in Fig. 14. In this case, the surface wind prior to the arrival of the disturbance was south-southeasterly averaging $2{\cdot}5\,\mathrm{m\,s^{-1}}$, but the pibal ascent at 0521 showed a shallow layer of southwesterly wind at heights between 100 and 300 m. With the passage of the disturbance, the surface wind backed abruptly to easterly, and increased to $6\,\mathrm{m\,s^{-1}}$, thereafter oscillating in strength.

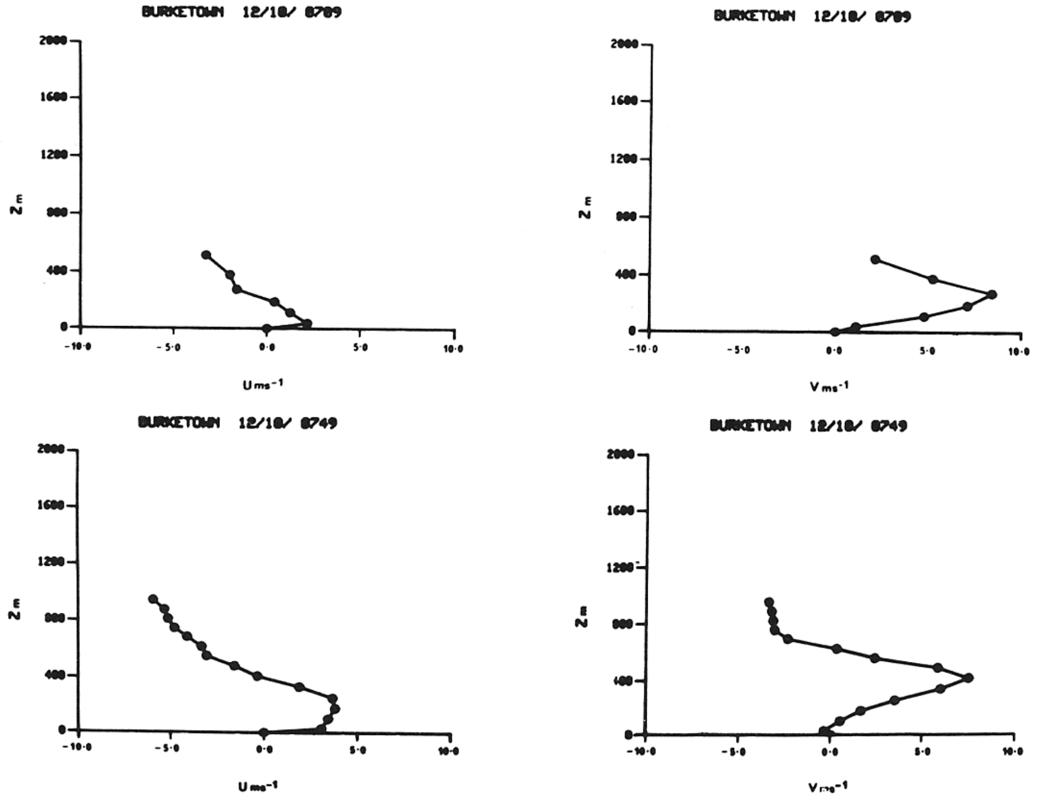


Figure 12 continued

Figure 13. View looking along the leading wave cloud of the morning glory of 13 October 1980 towards the southeast. The leaning trees give some indication of the wind strength associated with the disturbance. The photograph was taken about 25 km east of Burketown about 0600LST.

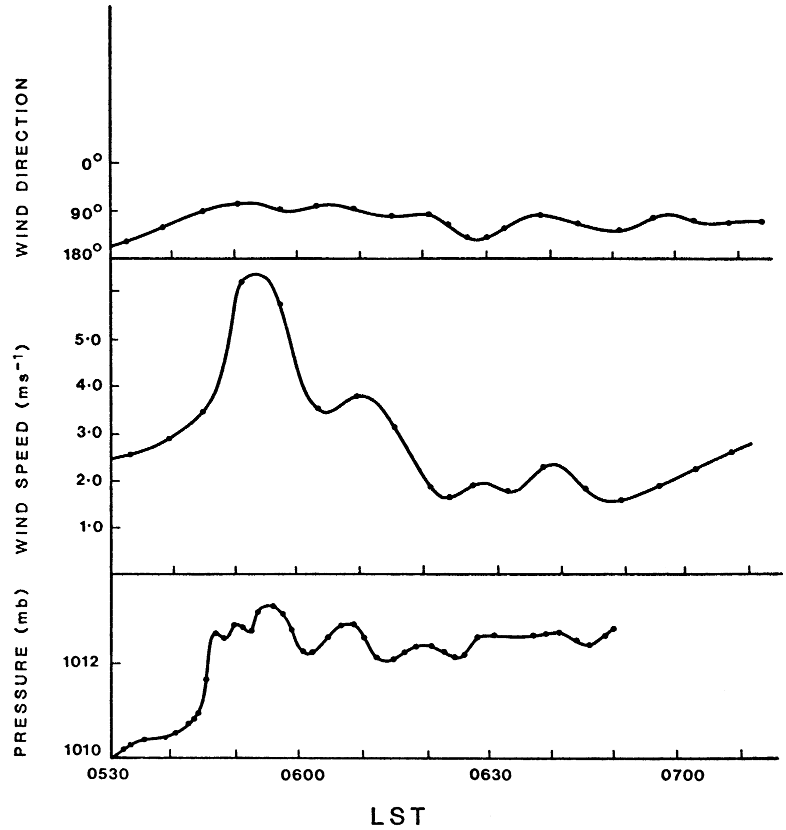


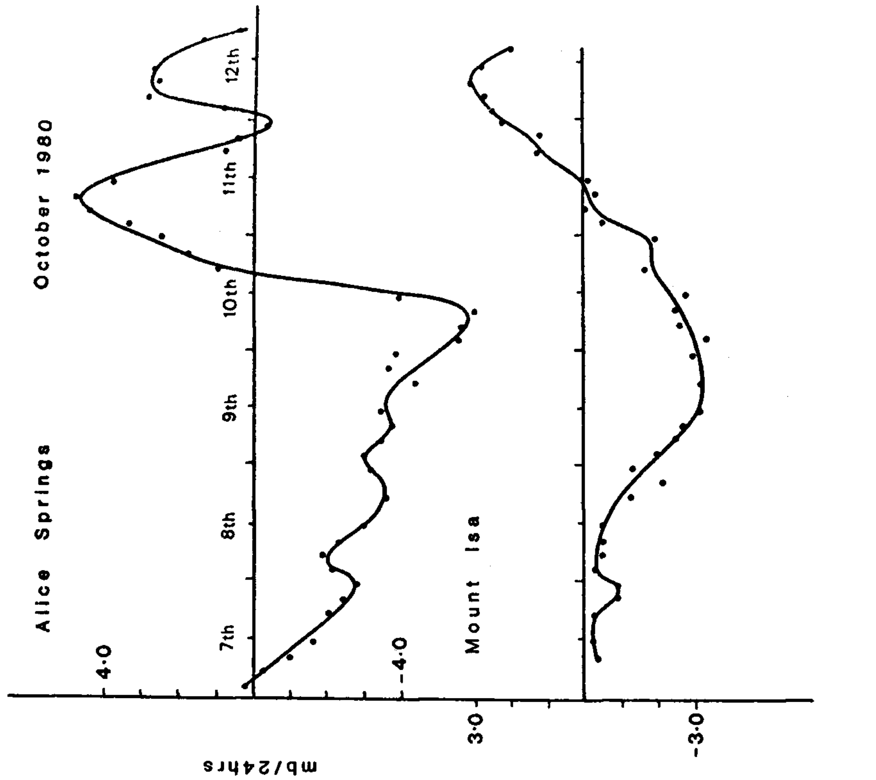
Figure 14. Surface data for 13 October 1980.

Single theodolite pibal ascents were made at 0521 and 0634, prior to and following the passage of the disturbance. Ahead of the glory, winds were southerly up to 100 m, southwesterly to 300 m, reversing to strong northeasterly above this level. After the passage of the disturbance, the winds below 400 m changed to easterly, but remained northeasterly above.

Unlike the preceding events, the cloud lines associated with this glory were visible on the Japanese Geostationary Meteorological Satellite (GMS) at 0700. The lines, which extended over approximately 100 km, were oriented along 45°/225°. Using this orientation and the passage times of the pressure jumps at Normanton (1·0 mb at 0255), Karumba (1·0 mb at 0308) and Burketown (0545), the average speed of the disturbance between these locations was about $12\,\mathrm{m\,s^{-1}}$.

3. Morning glory type occurrences in the Gulf of Carpentaria and elsewhere

We have no reason to believe that the sequence of morning glory occurrences at Burketown during the six day period 8–13 October 1980 was especially unusual for the time of year. Bureau of Meteorology barograph traces at Normanton and Mornington Island show that pressure jumps, presumably associated with morning glories, occur regularly from September to November, with jumps on consecutive days being common. Obviously, the



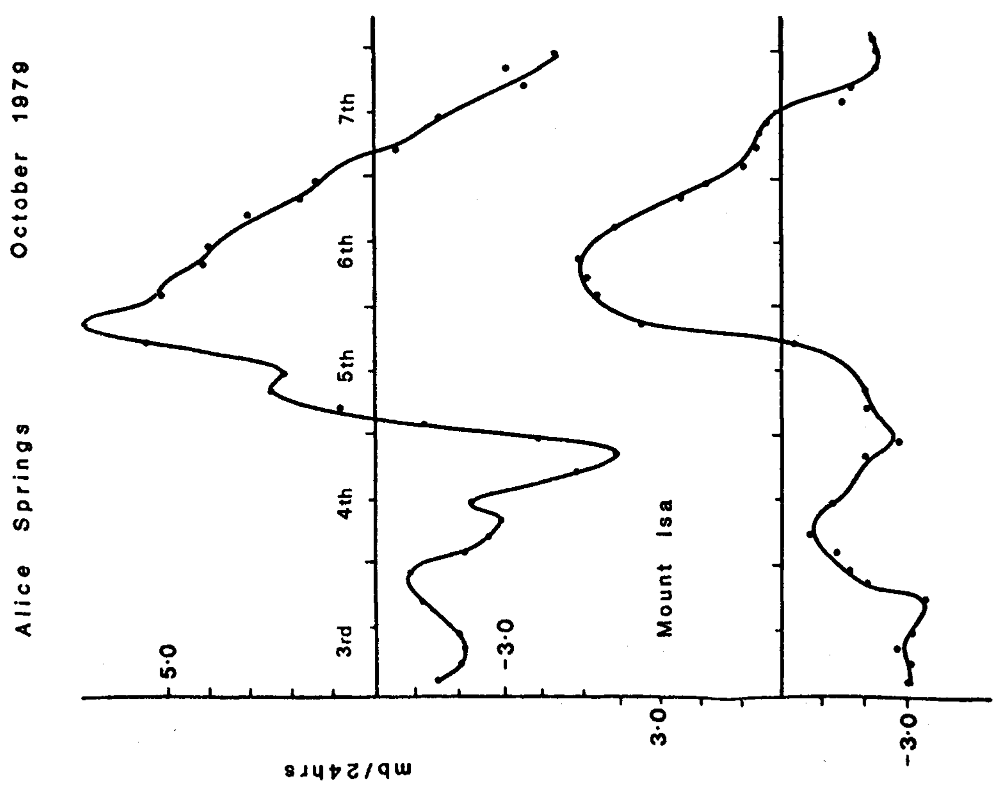


Figure 15. Twenty-four hour surface isallobars at Alice Springs and Mount Isa for a few days surrounding the occurrence of southerly morning glories at Burketown on 6 October 1979 and 9 and 12 October 1980.

southern region of the Gulf of Carpentaria is a particularly favoured one for morning glory type events, but it is intriguing that there are apparently two preferred sectors of origin of such disturbances, one centred about northeast and the other close to south. Also, since it is highly unlikely that southerly morning glories result from the same causes as those from the northeast, it is surprising that the hour of maximum frequency of occurrence of events at Burketown is the same for both sectors (the three southerly morning glories observed at Burketown, including that of 6 October 1979, occurred between 0600 and 0700, the hour of maximum frequency of those from the northeast). It is also remarkable that events from different sectors can occur on consecutive days, as in the six day period described in Section 2.

The origin of southerly morning glories is difficult to determine owing to the complete lack of data in the region south of Burketown and north of the Mount Isa area. Nevertheless, two of those we have observed, those of the 6th (1979) and the 12th, are presumably associated with disturbances which passed through the Mount Isa region the previous evening, and both occurred in advance of a frontal trough preceding the eastward movement of a high pressure system across central Australia. This is evidenced by time series of 24-hour surface isallobars at Alice Springs (24°S, 133°E) and Mount Isa (20°S, 140°E) for a few days surrounding each event (Fig. 15). Such time series give an indication of synoptic scale pressure changes, uncontaminated by the sizeable diurnal pressure changes at these latitudes. Significantly, the morning glories of the 6th (1979) and 12th occurred at Burketown within twelve hours of the onset of a period of sustained surface pressure rise at Mount Isa. The eastward progression of the anticyclone is apparent by the commencement of rising pressure a day earlier at Alice Springs. The southerly morning glory of the 9th cannot be identified with any disturbance in the Mount Isa region, nor with the passage there of a trough. The different appearance of this event compared with the other two might suggest a different generation mechanism and region of origin, but in the absence of further data, the uncertainties remain.

In view of the occurrence over the Gulf of Carpentaria of morning glories from at least two apparently different source regions, it would be surprising if such events were unique to the Gulf. Indeed, there is evidence that the phenomenon or closely related phenomena do occur elsewhere. For example, it seems likely that the spectacular long smooth low-level roll cloud reported by Robin (1978) is the same phenomenon. This cloud was observed in otherwise clear air, except for fragments of a second roll cloud parallel with it, over Spencer Gulf in South Australia. Also it occurred ahead of a frontal trough. Unfortunately, no surface wind or pressure data are available on this event. An apparently similar cloud line and accompanying wind squall, observed just after sunrise in eastern Russia, is reported by Novozhilov (1969). Novozhilov suggests that this cloud and squall are manifestations of a wave on the nocturnal inversion. He speculates that the wave might be generated by the progression of the terminator, but does not elaborate on this idea. He does not give any information on surface pressure changes during the passage of the cloud.

There are more numerous reports of disturbances unaccompanied by cloud with surface pressure signatures similar to those of the morning glory. Indeed, such disturbances, with propagation speeds and amplitudes consistent with boundary layer disturbances occur commonly at night in central Australia (Christie *et al.* 1979). Also, they have been the subject of numerous reports in Malta (Lamb 1954; Kirk 1961, 1963a, 1963b) where they are said to occur frequently (Kirk 1961). Other possibly related events are described by Tepper (1950), Matthews (1951), Pothecary (1954), Wagner (1962) and, more recently, by Shreffler and Binkowski (1981).

Tepper (1950) studies a case of a propagating pressure jump line in the United States in which surface pressure rises of 2·3 mb in 5 minutes were recorded. The line appeared to have been generated by, but was moving well ahead of, a surface cold front. Two well documented events, one in Malta analysed by Lamb (1954) and the other in Khartoum described by Matthews (1951), bear a remarkable resemblance to the morning glory. In each case, the microbarograph and anemograph records show a sharp surface pressure jump, followed for over an hour and a half by regular oscillations in pressure and wind velocity. In each case, the mean (uncorrected) surface pressure was higher after the passage of the disturbance than before. Also, the events occurred during the early morning in conditions where there was a low level inversion and in neither case does there appear to have been any significant temperature change at the surface. Of particular interest is Matthews' note that 'there was no marked change of air mass' and his suggestion that the disturbance was '. . . probably associated with a local movement of the intertropical front which was lying . . . through or near Khartoum'. The latter is reminiscent of the synoptic situation in the case of the two southerly morning glories of the 6th (1979) and 12th.

Another well documented event is that described by Pothecary (1954) in which a surface pressure jump and abrupt change in wind velocity, followed by an oscillation in pressure and wind, was observed to propagate over central and southern England during the night. Pothecary attributes this disturbance to the temporary blockage of a northeasterly airstream beneath an inversion by the outflow of cold air from an intense outbreak of thunderstorms over the English Channel. In contrast to this, Wagner (1962) describes the propagation of a large scale wave over New England in which the pressure rise was more gradual, but of the order of 2–4 mb in two hours, there being no local changes in weather with the passage of the wave.

Finally, Shreffler and Binkowski (1981) describe two surface pressure jump lines which passed through a dense mesometeorological network in the St Louis region of the United States on consecutive nights in August 1976. The data are unique, except for our own data on morning glories, in that they include frequent upper air measurements. Both pressure jumps, which ranged in strength between 1·2 and 1·8 mb in 6 minutes at individual stations, were accompanied by a temporary change in wind velocity, but no decline in temperature. Like the morning glory, they are clearly associated with disturbances on the low level nocturnal inversion. Shreffler and Binkowski suggest that they may have been generated as a result of intense thunderstorm activity along a quasi-stationary front across Iowa. If so, the pressure perturbations could be detected over 500 km from their origin.

4. Possible generation mechanisms

Owing to the paucity of data, it is inevitable that ideas relating to the genesis of southerly morning glories are speculative, but the occurrence of the events of the 6th (1979) and 12th just ahead of an advancing frontal trough offers a possible clue to their generation. It appears to be the experience of local forecasters that during the day, the north eastward advance of the frontal trough is often retarded, possibly by the enhanced intensity of the semi-permanent trough in an area just south of the Gulf due to strong solar heating. In the late afternoon and early evening, the heat trough weakens and the frontal trough accelerates. In such a situation, it seems plausible that the frontal surge into a developing nocturnal inversion ahead of it could generate an undular bore in much the same way that the east coast sea breeze on Cape York is believed to initiate morning glories from the northeast. Also, assuming the existence of a preferred location for the daytime heat trough, the preferred time of day for the onset of the pressure surge might explain why such disturbances reach the Gulf at about the same time the following morning.

The foregoing ideas are broadly in line with those of Tepper (1950) who argues that a cold front accelerating into a low level stable layer would, in certain circumstances, lead to a propagating wave-type disturbance which runs ahead of the front, eventually steepening to form a near discontinuity – a type of internal hydraulic jump, or bore. Weaker bores might be expected to assume an undular character in analogy with weaker ones on shallow water (see e.g. Benjamin 1962, §2; 1967, p. 576). While this mechanism, or a modification of it, seems to us to offer the most plausible explanation for the generation of the morning glories of the 6th (1979) and 12th, the data are not unequivocal. For example, on the 6th (1979), the northeastward advance of the trough is in evidence, but the trough axis has more of the character of a dry line, there being no marked temperature contrast across it, at least at the surface. On the 12th, however, the air behind the front was appreciably colder (by some 5–10 K in 200 km) than that ahead, but the cold air boundary became quasi-stationary with an almost east-west orientation, one or two hundred kilometres to the south of Mount Isa. In fact, it remained in this position throughout the night of the 11th and the morning of the 12th, even though there were 24-hour isallobaric rises at Mount Isa during this period as the high over central Australia continued to move eastward (see Fig. 15). It is, of course, possible that a local movement of the front, smaller than could be resolved by the synoptic network, could initiate a disturbance in the manner envisaged by Tepper (see also Matthews' remarks quoted in §3).

The efficacy of Tepper's mechanism in generating disturbances of the type observed does find support in several laboratory experiments in density stratified fluids (Maxworthy 1980; Baines 1981; and some of our own described below).

In the experiments reported by Baines (1981), a rectangular channel 9 m long, 0·35 m high and 0·23 m wide is filled through most of its depth with fresh water and then topped up with a much shallower layer of paraffin, forming a two layer fluid system. Gently rounded obstacles, mostly a little deeper than the paraffin layer, are then towed along the tank at the surface. For certain parameter values (towing speed, paraffin layer depth, density contrast, etc.) an undular-type bore becomes established in the paraffin layer, running along it ahead of the obstacle. One might surmise that, as far as the bore is concerned, there is nothing special about the obstacle being solid and that it should be possible to generate a similar disturbance by running a gravity current into a shallow stable layer, the flow configuration envisaged by Tepper. The first two authors have attempted such an experiment using Dr Baines' channel and we have been able to generate wave-like disturbances which run ahead of the gravity current, on the stable layer. A photograph of an experiment of this type is shown in Fig. 16.

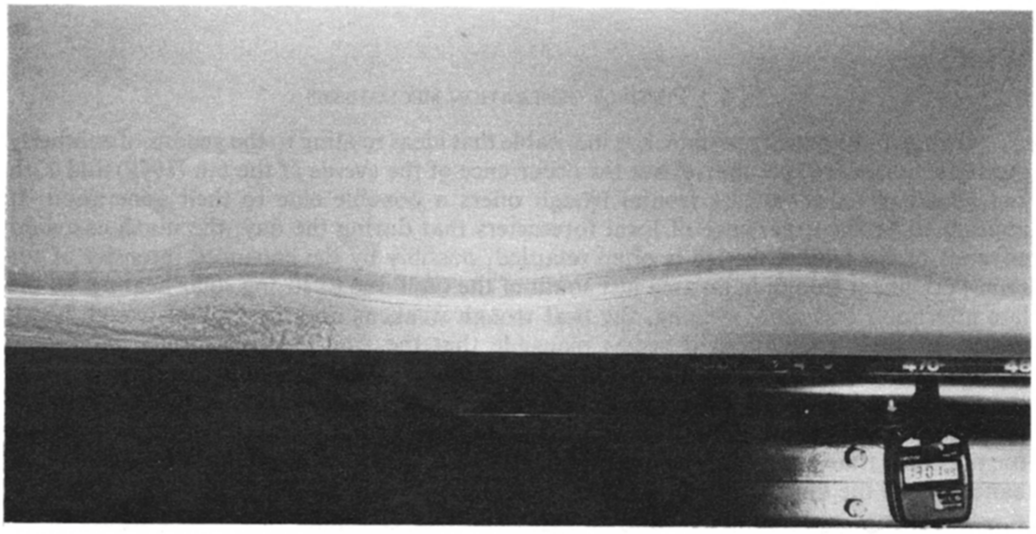


Figure 16. Density current propagating into a two layer fluid and creating internal waves ahead of it. The density current is formed by lifting the retaining wall of a dam filled with saline (density 1·02 kg per litre). The wall is lifted 5 cm above the bottom of the tank and in order to inhibit fresh water leaking into the dam, saline of the same density is pumped into the top of the dam. The two layer fluid into which the density current propagates consists of a layer of saline (density 1·01 kg per litre) 3 cm deep with a 32 cm layer of fresh water above.

The average speed of the density current was 6·0 cm s^{-1}, whereas the waves ahead of the density current moved at a speed of 8 cm s^{-1}.

Maxworthy (1980) has performed a range of experiments on intrusive-type flows in density stratified fluids, experience with which leads him to declare (p. 52) that '. . . if a physical system is capable of supporting solitary wave motions then such wave motions will invariably arise from quite general excitations . . .'. We presume that this contention would include finite groups of solitary-type waves associated with a dissipative undular bore such as the shallow water types studied theoretically by Johnson (1970, 1972) and Byatt-Smith (1971). These theories predict pressure signatures which closely resemble those observed during the passage of morning glories.

5. Discussion and conclusions

The observations described in §2 support previous observations on morning glories regarding the structure of these disturbances and show that a light surface wind with a westerly component is favourable to morning glory occurrence, even in the case of disturbances from the south. A unique data set on two southerly morning glories shows that these are structurally similar to those from the northeast, but in the three documented southerly events (including that of the 6th, 1979), the average propagation speed is about 15 m s^{-1}, significantly larger than for northeasterly glories for which the average is 10·2 m s^{-1} (Clarke *et al.* 1981; see Fig. 17).

A lack of sufficiently detailed data in the presumed region of origin south of Mount Isa makes it difficult to do more than speculate on the mechanism of generation of southerly morning glories. However, as discussed in §4, Tepper's mechanism, or a modification thereof, seems to us to offer a plausible explanation, at least for the genesis of the events of the 6th (1979) and the 12th.

Evidence is presented which suggests that morning glory-type phenomena occur widely, both in Australia and elsewhere, but it is clear from the events described in §2 that the Gulf of Carpentaria region is particularly favoured with regard to the frequencies of occurrences.

In our view, the morning glory and related phenomena must be viewed as more than just a meteorological curiosity. Although the wind squalls are not normally severe, compared, say, with severe thunderstorm outflows, their sudden onset, especially when unannounced by cloud, poses a serious hazard to light aircraft, particularly during landing and take-off. Moreover, our observations show that these disturbances are effective mechanisms for triggering deep convection in the Gulf region. It is clear also that the precursors to southerly morning glories, such as the disturbances which passed through Mount Isa on the evenings of the 5th (1979) and 11th, constitute an important analysis problem in northwestern Queensland; a situation similar to that in the Mediterranean area where pressure jump lines may be misleadingly analysed as fronts (Kirk 1961). This is presumably the case in other areas where morning glory-type disturbances occur. A good example is that of a cold front passage (designated event one) monitored during the first observational phase of the Australian Cold Fronts Research Programme in November/December 1980 in the Mount Gambier area of South Australia. This front was preceded by a propagating pressure jump and wind change line at the surface, several hours before the air mass change (Physick and Troup 1981). Such events have not been well documented before, but are of obvious meteorological significance, requiring detailed attention in synoptic analyses. This is especially true in southeastern Australia in summer when forecasts of wind changes are often crucial in deciding strategies to combat wildfires.

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