The Morning Glory of the Gulf of Carpentaria: An Atmospheric Undular Bore

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ABSTRACT

This paper presents the results of a field expedition mounted in late September/early October 1979 to investigate the structure and origin of the "morning glory" of the Gulf of Carpentaria in northern Australia. The morning glory is a line wind squall, accompanied by a pressure jump, and often by a long roll-cloud or series of such clouds. It frequently occurs in the early morning, especially in October, in the Gulf area.

A light aircraft, fitted with a temperature and humidity probe, was flown in two glories to determine their thermodynamic structure, and wind fields were obtained principally by tracking pilot balloons using the double theodolite method. Data also were obtained from a network of surface stations, recording wind velocity and pressure, installed at locations across Cape York Peninsula, which is believed to be the area of genesis.

The morning glory is identified as an internal undular bore propagating on the nocturnal and/or maritime inversion. Its origin appears to lie frequently in the interaction of a deeply penetrating sea breeze front with a developing nocturnal inversion, but there is evidence also that on occasion it may result from the effect of a katabatic flow. The factors which appear to make the Gulf region particularly favorable for the common occurrence of this phenomenon are discussed.

1. Introduction

The "morning glory"[1] is a wind squall or succession of wind squalls, frequently accompanied by a spectacular roll cloud or clouds, occurring early in the morning, mainly in spring, at places around the southern coast of the Gulf of Carpentaria (latitudes 12–18°S) in northern Australia. The cloud bands may be up to a few kilometers across in the direction of travel, usually from the east to northeast, and are of considerable lateral extent, often stretching from horizon to horizon with a remarkably uniform cross section. The height of the cloud tops is not well known, but probably does not exceed 2500 m on most occasions, and the clouds rarely produce precipitation. Occurrences over the Gulf itself are poorly documented, but cloud lines there are common in satellite imagery and squalls accompanied by cloud lines are well known to fishermen and to Royal Australian Navy personnel operating there. A photograph of a morning glory cloud line advancing toward Burketown, North Queensland, at about 0900 LST[2] on 4 October 1979, is shown in Fig. 1.

To our knowledge the earliest published description of the morning glory appears in the Royal Australian Air Force (1942, Part 2, p. 25), where it is said to be a "land breeze" coming out of the east about dawn with a squally onset and with one or several long straight lines of low cloud.

Thirty years later, one of the present authors (Clarke, 1972) explored the possibility that the phenomenon could be interpreted as a propagating internal hydraulic jump, formed at a discontinuity in the slope of the ground, on a katabatic flow developing on Cape York Peninsula. The theory

[1] Anthropologist Dr. Margaret Moore informs us that the name of the phenomenon in the language of the Garrawa Aboriginal people who live near the south coast of the Gulf is "kangólgi," and it is credited with increasing the supply of bird life. This may reflect the fact that the morning glory occurs most frequently in October, just prior to the "wet" season, which is a harbinger of bounty for the Aborigine.

[2] All times in this paper are quoted in local standard time [LST = GMT + 10 h].

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FIG. 1. Morning glory cloud line approaching Burketown, North Queensland, at about 0900 LST on 4 October 1979.

relating to such jumps in shallow and deep layers of stratified fluid is described by Benjamin (1966, Section 3.8; 1967, p. 576). In a simple one-layer numerical model, Clarke showed that the simulated downslope flow developed two such jumps, one moving upstream and one moving downstream from the discontinuity in slope, the latter at a speed of 8–10 m s^{-1}, marked by a discontinuity of pressure and wind. Subsequently, this jump developed undulations over a limited region on the deeper side. These, however, were attributed to the finite differencing. The theory was inevitably tentative, since the only available data against which it could be compared were a series of autographic records of surface pressure, wind and temperature at the (now abandoned) weather station at Karumba (see Fig. 2). Moreover the theory did not take account of the strong heating contrasts between sea and land in the Gulf region and there appeared to be the possibility that the sea breeze circulation might be a more important influence than the katabatic flow.

More recently, Neal *et al.* (1977a,b) have presented a study of pressure jumps recorded on weekly Bureau of Meteorology barographs around the Gulf at Edward River, Kowanyana, Normanton, Burketown and Mornington Island (see Fig. 2). These data enable estimates to be made of the speed and orientation of a number of pressure jump "lines," presumably associated with morning glories. It is shown that the majority of lines were roughly parallel with the east coast of the Peninsula (and also to the coastal ranges which rise to a height of between 300 and 500 m in the Dividing Range) and move with a speed of typically 10 m s^{-1}. A climatology of pressure jumps also is given, showing frequencies of occurrence at the five stations in terms of time of day and month, and mean synoptic MSL isobaric charts for pressure jump days and for days free of jumps. The latter were classified according to whether surface winds were southeasterly or northeasterly in the southeast Gulf area. However, the isobars for northeasterly days without jumps are virtually indistinguishable from those with jumps.

In October 1978, the first author and his wife staged a small expedition to the Gulf with a view to collecting more detailed surface data on morning glories as well as photographs and time-lapse movie film of the clouds. Ten days were spent in the field during which time four glories were observed, a frequency which, coincidentally, corresponds with the average frequency of presumed morning glories at Karumba in October, based on nine years of data (Neal *et al.*, 1977a). Two of these four occurred before daybreak; one was cloud-free; two had five parallel cloud bands and the other three. All had marked wind and pressure jumps. One was followed by car over 35 km and its speed measured at 11 m s^{-1}; another was photographed in time-lapse which revealed a rolling motion of the cloudband with upward motion at the leading edge and downward

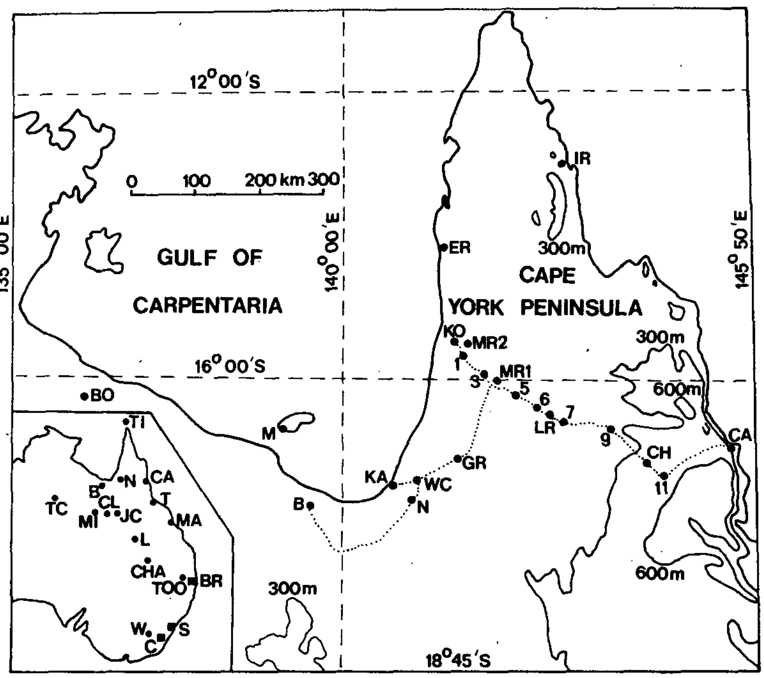

FIG. 2. Map of northeastern Australia, showing locations mentioned in the text, with topographic contours and the roads linking Cairns with Kowanyama, Normanton and Burketown. Abbreviations are as follows: B Burketown; BO Borroloola; BR Brisbane; C Canberra; CA Cairns; CH Chillagoe; CHA Charleville, CL Cloncurry; ER Edward River; GR Gilbert River; IR Iron Range; JC Julia Creek; KA Karumba; KO Kowanyama; L Longreach; LR Lynd River; M Mornington Island; MA Mackay; MI Mount Isa; MR1, MR2 Mitchell River, sites 1 and 2; N Normanton; S Sydney; T Townsville; TC Tennant Creek; TI Thursday Island; TOO Toowoomba; W Wagga Wagga; WC Walkers Creek.

motion at the rear. In each case, measurements of surface pressure, temperature, humidity and wind were made during the passage of the glory and some of the data collected is presented herein.

Early in 1979, a more ambitious expedition was planned with the partnership of the present authors and seven other participants. It had two main objectives: the first to observe the structure of morning glories, both in the horizontal and vertical, as they passed Burketown, with a view to identifying the mechanisms associated with its propagation and maintenance; the second to obtain surface data on Cape York Peninsula, believed to be the source region, in an attempt to identify the source and to understand the genesis of the phenomenon. The expedition lasted two weeks (23 September–5 October 1979) during which time three morning glories occurred at Burketown—at 0546 LST on the 29th, at 0700 LST on the 3rd and at 0935 LST on the 4th (hereafter, these occasions will be referred to as the 29th, the 3rd and the 4th). A disturbance was also observed on the morning of 6 October as the expedition party was about to leave Burketown, but no data were obtained, except photographs. An unprecedented amount of data was collected on the 29th and 4th, and its subsequent analysis, together with the data collected on Cape York, is presented in this paper.

About the same time as this latest expedition, and unbeknown to us until after the expedition, a paper by Christie *et al.* (1979) reported a study of intrusive-type flows and solitary waves in the lower atmosphere observed in microbarograph records at the Warramunga Seismic Station at Tennant Creek, ~600 km west-southwest of Burketown. In that paper, Christie *et al.* (1979, p. 4968) state that ". . . it seems very likely that the morning glory phenomenon is in fact a manifestation of a fairly well-developed large-amplitude isolated solitary wave or group of solitary waves. In this interpretation the roll clouds are associated with the closed circulation cells in the streamline pattern of large-amplitude deep-fluid internal solitary waves propagating along a marine inversion." As we shall show, our data broadly support this view.

The paper is divided into three main sections. In Section 2 we describe the structure of the morning glory as revealed by two detailed case studies, together with an analysis of surface pressure records for other occurrences. Following the identification of the phenomenon as an undular bore propagating on the low-level nocturnal or maritime inversion, the section concludes with an attempt to relate the observations to Benjamin's (1967) theoretical model for an undular bore in a deep fluid. In section 3 we consider aspects of the conditions which appear to be conducive to morning glory occurrence; this includes an analysis of surface pressure records from the Bureau of Meteorology's routine network in the Gulf region, a study of satellite imagery in the area, and a detailed analysis of surface observations gathered during the 1979 expedition across Cape York Peninsula. Finally, the origins of the morning glory, as revealed by the foregoing data, are discussed in Section 4.

2. Structure of the morning glory

a. The observations at Burketown

An eight-person team stationed at Burketown was divided equally into a ground-observer team and an aircrew.

The ground team performed double theodolite pilot-balloon ascents at appropriate intervals before and after the arrival of a morning glory as well as making the usual surface observations (pressure, temperature and humidity) and taking photographs. Surface pressure was measured at frequent intervals by means of a sensitive, manually operated digital aneroid barometer. In addition, a recording Woelfle anemometer, a thermograph and a hygrograph were installed at the observation site—the local airstrip.

The Clarke observations in 1978 indicated a typical quasi-period of strong wind gusts of 12–15 min during a glory passage. Hence, to optimize the horizontal wind resolution, it was aimed to release balloons every 5–10 min and, using helium-filled 20 g balloons with a mean ascent rate of $\sim$2.2 m s^{-1}, this imposed limitations on the depth of wind soundings in the disturbance, most of which were confined to below $\sim$1500 m.

The thermodynamic structure of the disturbance was investigated using a light aircraft—a twin-engined Beechcraft Travelair—with a Väisälä temperature-humidity probe mounted in the nose. Readings from this were recorded manually by one of two observers, working in conjunction with the navigator. The second observer's role was photography. Vertical soundings were made on spiral ascents and descents, ahead of and behind the disturbance, and thermodynamic data were also obtained during horizontal traverses[3] of the disturbance along its direction of motion. On these traverses, the pilot sought to maintain the aircraft as nearly as possible at constant attitude and power so that its vertical motion would give an indication of that of the air. A small tape recorder proved useful in obtaining a record of the flight path and in synchronizing data collection. It was used also to record altitude, indicated air speed and rate of climb, at about 10 s intervals during traverses.

[3] In some parts of the disturbances flown, organized vertical motions were appreciable so that, owing to the constant power and altitude configuration, vertical displacements of the aircraft during "horizontal" traverses were significant, being as large as 300 m on occasions (see Figs. 6 and 7).

The morning glory of the 29th arrived before daybreak, prior to the establishment of the second theodolite station. As a result, only single theodolite balloon observations were obtained in the vicinity of the leading edge of the disturbance, severely reducing the value of the wind data on this occasion.[4] However, aircraft penetrations of the disturbance were made and valuable thermodynamic data were collected, as well as data on the distribution of vertical motion within the flow. An aerial photograph of this morning glory taken $\sim$50 min after it has passed Burketown is shown in Fig. 3.

The morning glory which occurred on the 3rd was unaccompanied by cloud, but was recorded as a morning glory with a line of cloud at Mornington Island. At Burketown the wind changed suddenly from west to east and rose sharply to over 9 m s^{-1}, while the temperature and relative humidity changed almost instantaneously by +2°C and −22%.

The morning glory of the 4th, which had five cloud lines in all, was investigated in considerable detail. Ten double theodolite balloon soundings were made, giving vertical wind profiles from 20 km ahead of the leading edge to 50 km behind. Six of these soundings, beginning at intervals of $\sim$10 min, were reasonably adequate to describe the wind field in and between the first two cloud lines, extending for $\sim$20 km from the leading edge. Excellent time-lapse movie sequences were obtained also showing clearly the rolling motion of the clouds. Six aircraft traverses were made, ranging in altitude from 100 m to $\sim$1800 m and from 5 km ahead of the leading edge to 20 km behind. Vertical soundings ahead of and behind the disturbance also were made, but those behind could not be located with sufficient accuracy relative to the leading edge of the disturbance (as could all other data) to be used (see later).

Further details of the activities of the Burketown team are given by Smith and Goodfield (1981).

b. Pre-morning glory soundings on the 29th and 4th

Figs. 4 and 5 show the vertical wind and thermodynamic structure of the air ahead of the morning glories on the 29th and 4th, respectively. These data include profiles of virtual potential temperature θ_v, total static energy E, and wind components u and v

[4] See Section 2b.

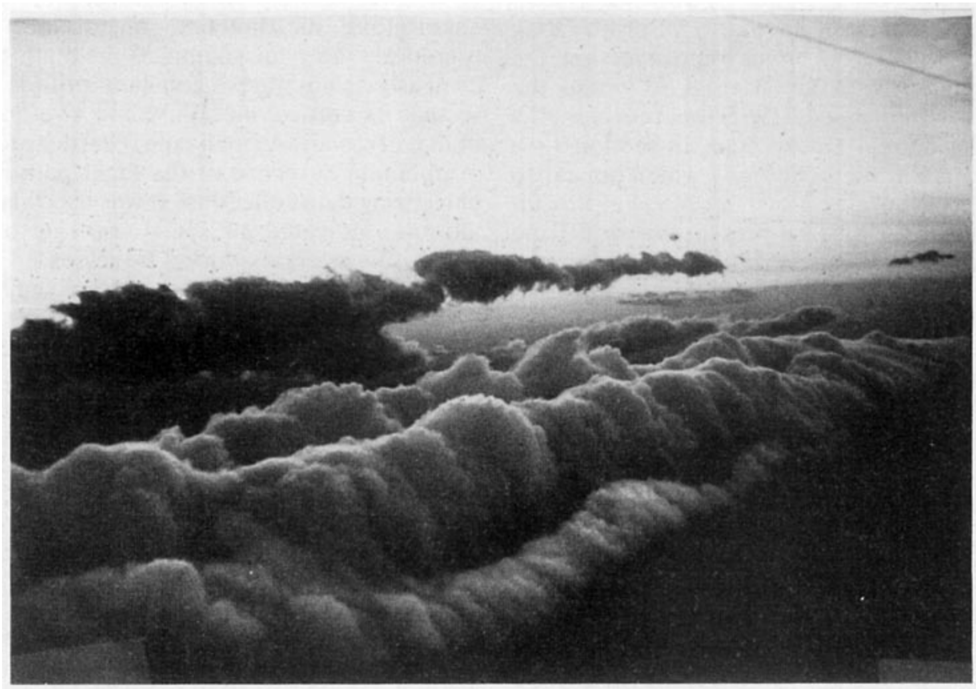

FIG. 3. Aerial photograph of the morning glory of 29 September 1979 just west of Burketown at about 0630 LST, looking toward east-southeast.

normal to and parallel with the cloud lines. Here $E = c_pT + gz + Lq$, where c_p is the specific heat at constant pressure, T temperature, g the acceleration due to gravity, z height, L the latent heat of condensation and q water vapor mixing ratio; this quantity, also called the moist static energy, is exactly conserved for steady frictionless air motions, even in the presence of condensation or evaporation. Line segment approximations to the θ_v profiles are used to compute characteristic Brunt-Väisälä periods, $2\pi[(g/\theta_v)\partial\theta_v/\partial z]^{-1/2}$, in each of two layers. The lowest one, having a characteristic period of 4–6 min, corresponds with the nocturnal inversion layer and is overlain by a much deeper layer of less stable air with characteristic period of ~14 min. The decay of total static energy with height shows this air mass to be potentially unstable; i.e., sufficient lifting will bring about moist static instability. On the 4th, potential instability is more pronounced, the top of a 300 m deep moist layer being very well marked. On both occasions, the wind is *toward* the glory in a shallow surface layer, but away from it at higher levels; however, the relative wind is toward the glory at *all* levels.

c. Observed structure on the 29th and 4th

Figs. 6 and 7 show vertical cross sections of θ_v along the line of travel for the two disturbances and Figs. 8 and 9 show the corresponding distributions of mixing ratio. In each case, the thermal and moisture fields are strongly perturbed and the isopleths of θ_v show that 20 km behind the glory, the cold boundary layer is deeper than in front of it. It is pertinent to note that the assumptions necessarily underlying the construction of the cross sections are that there is no temporal variation following the disturbance and no spatial variation along it. The first (and probably the second) is violated on the 4th, when strong low-level heating and mixing occurred over land between the ascent (at 0825) some 30 km inland, and the traverse (at 0947) which had to be made near the coast. Thus the subsidence implied by the descending isopleths on Figs. 7, 9 and 10 preceding the glory is almost certainly spurious.

The cross section of E is shown in Fig. 10 for the morning glory of the 4th; it is evident from this that low-level air is raised at least 1000 m as a result of the disturbance. The corresponding data for the 29th (not shown) are more difficult to interpret as the initial distribution of E is more uniform.

The cross-section distributions of wind components relative to the disturbance, $u - c$, where c is the speed of the disturbance, and the transverse component v are shown for the 4th in Fig. 11. The projections of the balloon trajectories on which this diagram is based are also shown. Note that subsidence is strong enough in parts of the disturbance to cause balloons with a relative speed of ascent of 2.2 m s^{-1} to descend. This highlights the need for double theodolite observations and leads us to reject the data from two single theodolite ascents obtained near the leading edge of the morning glory on the 29th. Two features are of particular significance in Fig. 11: first, it is clear that only small areas of the first two waves or rolls show positive wind relative to the front; second, wind speeds transverse to the direction of motion are appreciable—at least 4 m s^{-1}—in the vicinity of the leading roll as is apparent in the helical striations in the cloud pattern (Fig. 1). The more extensive area of transverse motion to the rear of the disturbance apparently was associated with a tendency for the wind to back toward late morning, presumably a manifestation of the strengthening sea breeze circulation.

The distribution of vertical velocity in cross section, as estimated by altitude changes of the aircraft, is shown in Fig. 12 for the 4th; values range up to 5 m s^{-1}, both positive and negative, consistent with deductions from balloon trajectories, assuming a relative rate of rise of 2.2 m s^{-1}. On the 29th, updrafts and downdrafts as high as 9 m s^{-1} were experienced at ~500 m. Corroboration of vertical velocities from the streamline pattern (see below) for the 4th is not good owing to the lack of sufficient horizontal resolution in the balloon data; it is not possible at all for the 29th as most of the wind determinations were made with a single theodolite.

The relative streamlines for the 4th, derived from the field of $u - c$ in Fig. 11 using the formula

$$\psi(x, z) = -\int_0^z (u - c)dz,$$

are shown in Fig. 13. These show an ordered train of waves with air flowing through the disturbance everywhere except within small closed cells in the first two waves, where it is carried along with the disturbance. A comparison of the wind and thermodynamic fields suggests that the coarseness of the wind soundings leads to an underestimate of wave amplitude as judged from Fig. 13, but the overall picture remains valid.

Surface observations on the 29th and 4th are displayed in Figs. 14 and 15, where the time axis has been transformed to distance for comparison with the aircraft data. On each occasion, temperature and humidity increase abruptly at the leading gust front of the disturbance, a result of violent stirring of a very shallow surface inversion layer. This has been observed previously as normal behavior at Karumba, Normanton and Burketown. However, surface wind and pressure changes differ markedly in the two events. Data for the 29th show a sudden jump in pressure and a change in wind

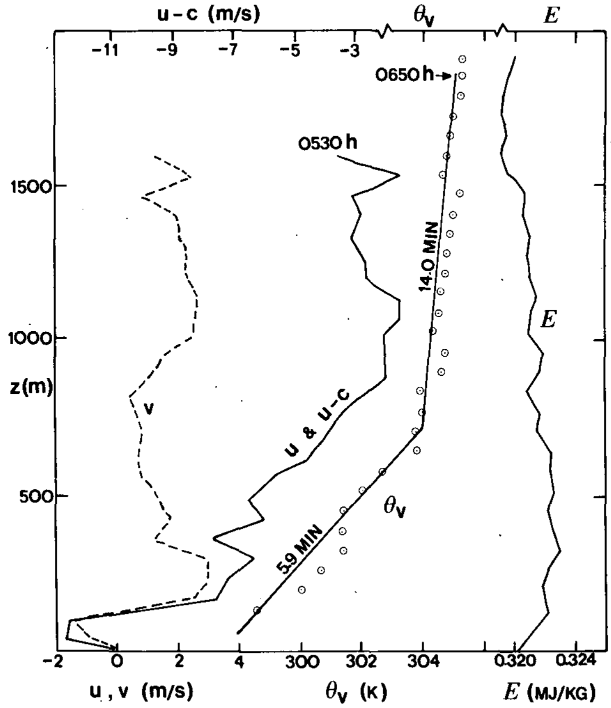

FIG. 4. Wind components (u and $u - c$) normal to the morning glory and (v) parallel to it; virtual potential temperature θ_v; and moist static energy E in the preglory soundings, 29 September 1979. The component u is positive in the direction of motion of the disturbance (towards 220 deg.) and v is rotated anticlockwise from it. Line segment approximations to the θ_v profiles are used to compute characteristic Brunt-Väisälä periods, shown in minutes, for the two layers shown. The velocity of the glory, c, is 10.8 m s^{-1}, towards 220 deg.

direction from south to east, sustained for 25 min, before reverting to southwesterly. On the 4th, the pressure rises abruptly and then oscillates as a succession of quasi-periodic waves, ordered in amplitude, with the largest first. In addition, changes in wind speed and direction respond to the pressure gradient in a consistent manner. In both cases, the pressure curves have been corrected by subtracting the diurnal changes obtained by averaging pressures at hourly intervals for a large number of October days. This is necessary because of the large diurnal and semidiurnal pressure variations at these latitudes due to other influences (Butler and Small 1963; Lindzen 1967). Of particular significance is the fact that the adjusted pressure rises sharply with the passage of the glory and *remains* higher (see Section 2d).

Clouds and turbulence were noted during the aircraft traverses although judgements of turbulent intensity were necessarily subjective. On the 29th, the morning glory cloud band extended from a base at ~360 m to a top at 1300 m and when first observed was nearly 4 km wide. Subsequently, it dissipated rapidly, while maintaining speed, and remained

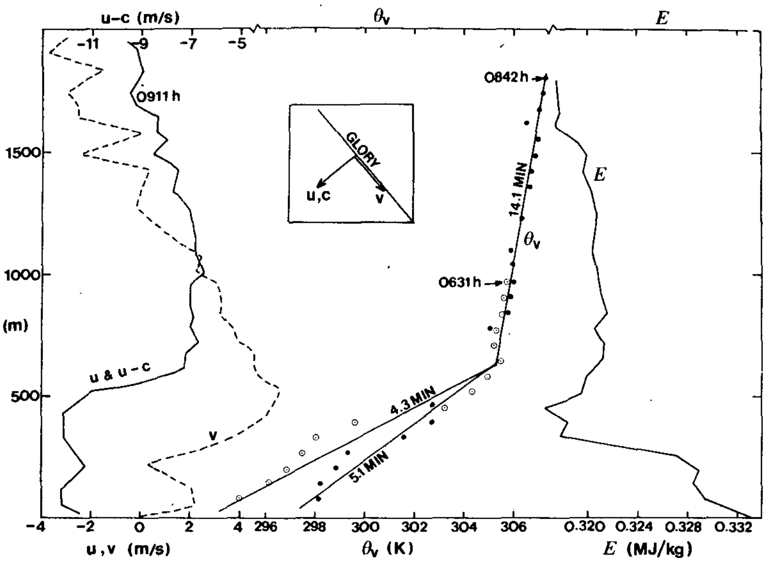

FIG. 5. As for Fig. 4, for 4 October 1979. Two soundings are shown in the lower layer, with Brunt-Väisälä periods as indicated. The morning glory was moving towards 230 deg. at 9.0 m s^{-1}. The coordinate system for u, v is shown inset.

visible for some time as a chain of separate cloud segments. On the 4th, the leading cloud roll had a base at 740 m and a top at ~1900 m when first encountered, but while it was under observation, its width decreased over 1 h from 4.1 to 1.9 km. On both days, turbulence was, for the most part, notably slight and the impressive deviations from the horizontal flight path were clearly associated with the organized wave flow. There were on the 29th, however, some patches of light to moderate turbulence on flight paths below 1500 m in the region −15 to −20 km (see Fig. 6), especially on the uppermost path, to one side of which there was a patch of ragged cloud, presumably marking a second wave crest. Also on this day, there was a sharp wingdrop during rapid descent near the position (−3,500).

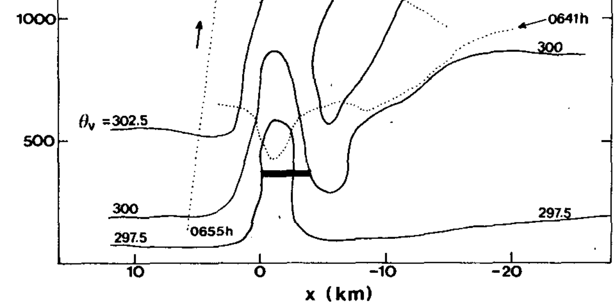

FIG. 6. Cross-section of virtual potential temperature θ_v, through the morning glory of 29 September 1979. Flight paths of the aircraft are shown by dotted lines. Estimated positions of cloud base and top are shown by heavy lines.

Further data on the cloud were obtained for the morning glory of the 4th by a photogrammetric analysis of the time-lapse movie sequences, taken as the disturbance approached Burketown. In the film, cloud elements were seen to be moving upward and laterally on the leading cloud face, in a curved path, indicating decreasing upward velocity toward the top of the cloud and fairly constant motion along it. Velocity estimates for these elements give a vertical velocity of 4.8 m s^{-1} near cloud base, decreasing to zero at the top, and a lateral horizontal velocity of 4.0 m s^{-1}. These estimates agree well with the aircraft data (Fig. 12), where vertical velocities of 5 m s^{-1} between heights of 400 and 900 m were inferred in the leading updraft, and with the balloon winds, which showed lateral horizontal wind components of 3–5 m s^{-1} between 300 and 1000 m in the pre-glory soundings. The height of cloud base (at 0902 LST) was estimated as 750 m and the top as 1900 m. The rapid decay of the cloud lines as they approached Burketown is very apparent in the film.

d. Surface pressure behavior for other cases

As found by Neal *et al.* (1977a,b), pressure jumps of the type long known to occur at Karumba, and presumed to be associated with morning glories, also have been detected at five other locations: Edward River, Kowanyana, Normanton, Burketown and Mornington Island, on standard weekly barographs maintained by the Bureau of Meteorology. The traces are of generally good quality, but the instrument response is such that post-jump waves are not recorded and the times of occurrence of jumps cannot be accurately determined. This is an unfortunate limitation for mesoscale studies. During the 1978 and 1979 expeditions, a few more detailed morning glory pressure signatures were obtained; these are shown in Fig. 16. Five of these were measured with a manual digital aneroid barometer and the remaining three with a version of the same instrument recording at 3 min intervals. They have all been corrected for mean diurnal and semidiurnal variations as described above. Of course, it also would be desirable to eliminate the effects of synoptic-scale changes, but this is not possible.

It is evident that each disturbance is characterized by a pressure rise with attendant, sometimes extensive, embroidery, ranging from the wavelike patterns of the mature jumps of 4 October 1979 and 14 October 1978 to the relative simplicity of that of 29 September 1979. In all of the traces, except perhaps that for 7–8 October at station 1, the corrected pressure remains substantially higher than before the jump, at least for some time. To test this conclusion more widely, a comparison was made at three places between $\delta_3 p$, the pressure change during 3 h from just before a pronounced pressure jump, and $\delta_3 p_c$, the same change corrected. The results are given in Table 1. At the three stations considered the pressure does remain generally higher 3 h after the jump, a result which we shall show to be of some significance.

Expedition data from the periods 6–10 October 1978 and 23 September–10 October 1979 have enabled us to determine the speed and direction of the pressure jumps. The assumption is made that pressure jump lines are straight and move at constant speed. Where more than three station times of passage are available, the values of speed and direction are obtained by least-squares fitting. Fig. 17 shows the velocities so obtained, with the number of data points on which they are based. It should be remarked that these are mainly based on pressure data, except that at wind stations over the Peninsula, a sudden change of wind, if it appeared in sequence, was taken as evidence of at least an incipient pressure jump. However, it transpired that on the occasions when these could be used, it made no significant difference whether only available pressure jump times were included, or whether the times of wind signatures were also incorporated.

One day (6 October 1979) with a sharp pressure jump at Normanton and Mornington Island, on which a morning glory was observed at 0700 LST at Burketown, moving from the south, has been omitted from Fig. 17. The propagation speed of 16.3 m s^{-1} toward 20° contrasts sharply with the other velocities. Examination of synoptic charts show that the cloud line lay in the axis of a pronounced MSL trough, at least 1000 km long, and moving from the southwest on the northeast side of an advancing ridge of high pressure. Some aspects of this disturbance are discussed by Christie *et al.* (1981).

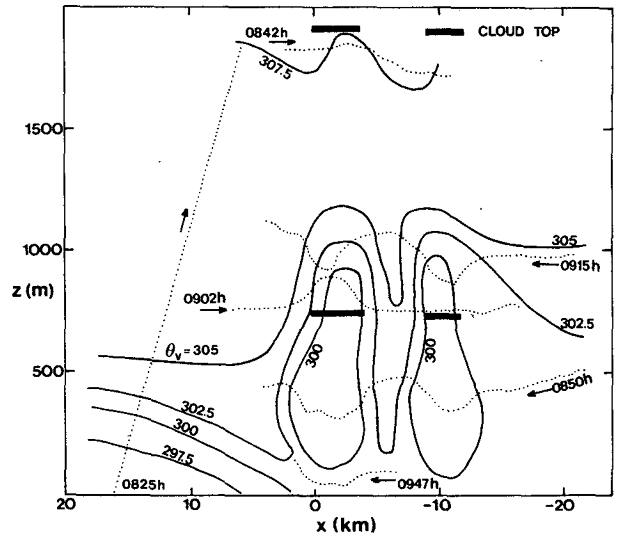

FIG. 7. As for Fig. 6, for 4 October 1979.

e. Inferences from the data

Based on the data presented in Sections 2b–2d, we conclude that the passage of a morning glory is characterized at the surface by a pressure jump, by a surface wind rising to a maximum about the time of maximum pressure change, and by a rise in temperature and often in absolute humidity. The glory frequently is accompanied by a long straight cloud line, or series of such lines, moving from the east to northeast. The speed of movement, based on a sample of 15, is 10.4 ± 1.5 m s^{-1}, and its vector mean orientation is 330–150°, essentially parallel with the east coast of Cape York Peninsula. In disturbances accompanied by cloud, the cloud base is close to the lifted condensation level of the lowest 10 m of air. The vertical development of the clouds must be related to the height through which the stable low-level air is lifted by the disturbance. In the two case studies presented in Section 2c, cloud tops lay below 2 km, and visual observations and photographs of many other glories lead us to believe that this is about the limit of development of the cloud rolls. However, if sufficient conditional instability is present, the morning glory may trigger and leave behind large congestus or even cumulonimbus clouds over the Gulf.

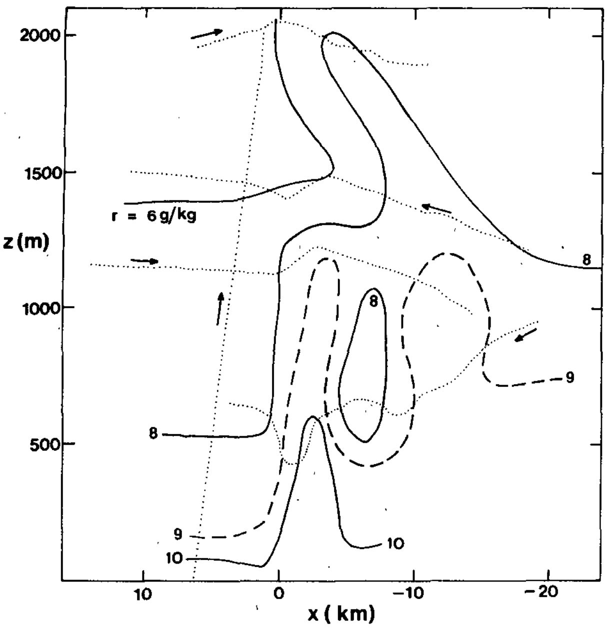

FIG. 8. Cross-section of mixing ratio, 29 September 1979. Units are g·kg⁻¹.

Surface winds so far measured have nowhere been found to exceed the speed of translation of the system, and their direction during gusts is very close to being normal to the glory orientation. Over the sea, surface winds are presumably stronger than over the land, but it is not known whether they can exceed the speed of translation at the gust front.

It appears that glories only occur in an atmosphere which is very stable in a shallow layer near the ground, such as occurs in the nocturnal or maritime inversion in the Gulf area. The relative streamlines in the one well-documented case showed a small closed circulation in the first two waves at heights within the preexisting inversion. Although of poorer quality, the wind data for the glory of the 29th, together with the aircraft data, suggest that this event probably has a region of closed relative circulation also. Fluid trapped in the recirculation region on the 4th, and what is presumably the recirculation region on the 29th, has the properties of the undisturbed air at very low altitudes, perhaps below 50 m.

The density and flow structure show conclusively for both cases that the morning glory is not a gravity current, a characteristic of which is a low-level feeder flow toward the leading edge of the disturbance (see e.g., Simpson *et al.*, 1977, p. 59); most of the relative flow is *through* the system, which contains very little advected fluid. A few kilometers behind the leading edge the relative flow is away from it at all levels; i.e., the disturbance moves faster than the wind at any height (at least up to 2 km, below which height the disturbance appears concentrated). Evidently, the disturbance has the characteristics of a traveling wave or group of waves, but the pressure rise accompanied by the disturbance is sustained, generally for well over 3 h, even when allowance is made for the normal diurnal pressure variation. Thus, the structure is consistent with that of an internal undular bore of the type described by Benjamin (1967, p. 576), propagating on the nocturnal or maritime inversion. Briefly, an undular bore is a weak hydraulic jump in which most of the energy lost at the jump is radiated away downstream (relative to the jump) by waves, in contrast to a strong jump where it is dissipated by intense turbulence generated at the jump.

The above finding confirms the view of Clarke (1972, p. 311) that ". . . the morning glory is a propagating undular hydraulic jump . . ." and, with qualification, of Christie *et al.* (1979); see last paragraph of Section 1. By "solitary wave," Christie *et al.* presumably include the "periodic wave" described by Benjamin (1967, Section 3.5), the deep fluid counterpart of an internal cnoidal wave (Benjamin, 1966), of which the solitary wave is a special case.

As far as we are aware, the morning glories of the 29th and 4th are the first well-documented examples of undular bore-type phenomena in the atmosphere; the only other identifications known to us being those described by Christie *et al.* (1979). The latter were based on data obtained from an infrasonic microbarograph array located at Tennant Creek in central Australia. Some of the pressure signatures of disturbances observed at Tennant Creek show a remarkable similarity to those characteristic of morning glories as shown in Fig. 16. They also occur at night and since the observed phase speeds and

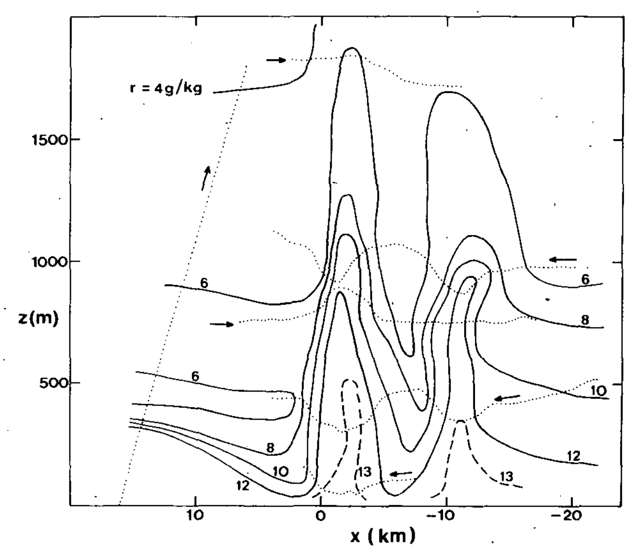

FIG. 9. Cross-section of mixing ratio, 4 October 1979.

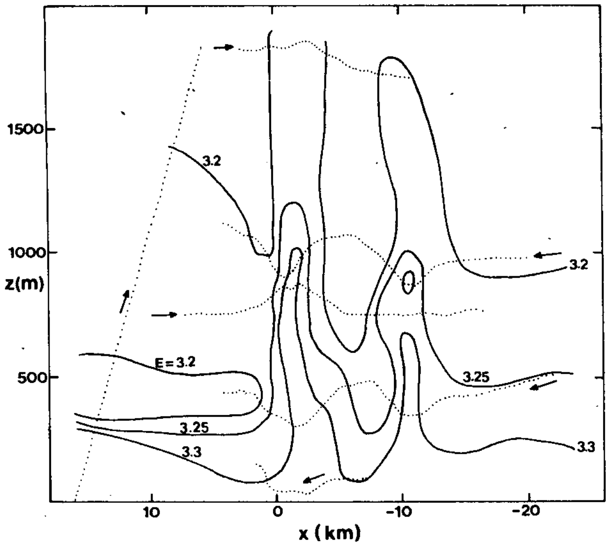

FIG. 10. Cross-section of moist static energy, E, 4 October 1979. Units are 10^5 J·kg^{-1}.

amplitudes are consistent with a boundary-layer disturbance, Christie *et al.* conclude that they correspond with disturbances which propagate along the nocturnal radiation inversion. Apparently, these disturbances are rarely, if ever, associated with cloud and, unlike the morning glory, produce only minor perturbations in the atmospheric flow field at the surface. For the latter reason, Christie *et al.* infer that most of the energy of the disturbances is concentrated near the nocturnal boundary-layer interface.

Before considering the data gathered on Cape York Peninsula and, indeed, before attempting to relate Benjamin's theory to our observations, it is appropriate to consider a way in which the morning glory might originate. As noted earlier, Clarke (1972) proposed the katabatic drainage flow over Cape York Peninsula, west of the Dividing Range, as a generation mechanism. This idea was supported by the results of a simple one-layer numerical model in which a simulated downslope flow developed a disturbance, marked by a sharp change in pressure and wind. This disturbance subsequently moved over level ground, away from the discontinuity in terrain slope near which it formed, and developed undulations over a limited region on the deeper side. Although Clarke attributed no great physical significance to these undulations owing to their sensitivity to the mesh size used in finite differencing, this type of behavior would now be anticipated from recent theoretical studies. Such theories are reviewed succinctly by Christie *et al.* (1979) and here we describe only the salient features.

The evolution of a general disturbance in a strongly stable layer of fluid underlying a much deeper layer of homogeneous or weakly stable fluid is governed by the Benjamin-Davies-Ono (BDO) equation (Ono, 1975; Grimshaw, 1981a), provided the disturbance amplitude is small compared with the depth of the underlying layer. The BDO equation has, *inter alia,* periodic solutions and solitary wave solutions (solitons) of permanent form as detailed by Benjamin (1967). Moreover, calculations suggest that a general initial disturbance of finite extent will evolve into a finite discrete set of solitons and an independent dispersive wave train. The solitons are ordered in amplitude as larger waves travel faster.

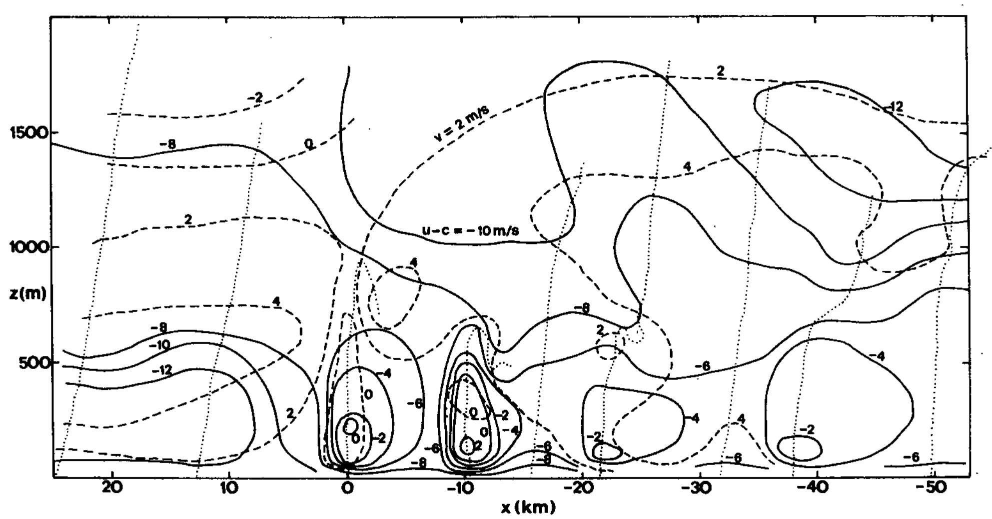

FIG. 11. Cross-section through the morning glory of 4 October 1979, showing isotachs in m s^{-1} of $u - c$, the normal wind relative to the moving system, and v, the transverse component (broken lines). Pilot balloon trajectories in the moving coordinate system are shown by dotted lines. The speed of translation of the glory, c, is 9.0 m s^{-1} towards 230 deg.

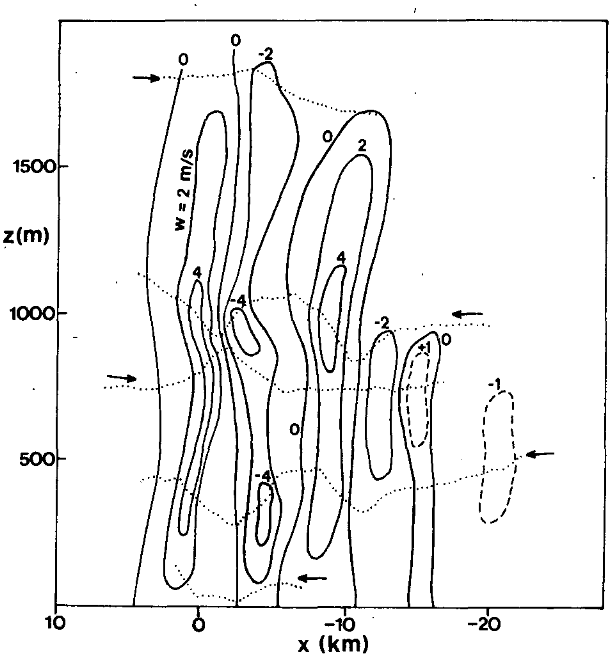

FIG. 12. Cross-section for 4 October 1979, showing vertical velocity component w in m s^{-1} as esimated from the aircraft response.

This evolution process is illustrated by Christie *et al.* (1979, Fig. 2). Presumably, the undular bore as conceived by Benjamin (1967, see especially Fig. 5) represents a stage in the evolution process described above. These theoretical results also find support in laboratory experiments; indeed, experience from these leads Maxworthy (1980, p. 52) to declare ". . . if a physical system is capable of supporting solitary wave motions then such motions will invariably arise from quite general excitations." On the basis of all these studies, it seems reasonable to infer that the morning glory, as observed at stations as far west as Burketown, represents an intermediate stage in the evolution of a disturbance originating further to the east or northeast, which would, if the stable surface layer remained essentially unchanged, continue to develop into a succession of isolated solitary waves. The origins of the disturbance itself are considered in Section 4.

f. Comparison with theory

At this point it is instructive to attempt a comparison of the morning glories observed on the 29th and 4th with the wave solutions given by Benjamin (1967). Benjamin's model relates to wave motions in a layer of stably stratified fluid of uniform depth h and density $\rho(z)$, underlying an infinitely deep layer of homogeneous fluid with density $\rho(h)$. In the model, the fluid in both layers is at rest, but it is straightforward to generalize the results to the case where there is a basic horizontal flow $U(z)$ and this is necessary for our purpose. It is assumed that each streamline is horizontal far upstream from the disturbance and has a vertical displacement $\zeta(x, z)$ from its upstream height z at a horizontal position x, measured in a reference frame moving with the wave at uniform speed c. Disturbances are assumed to be independent of the cross-stream direction, normal to x and z. Then, in the lower layer, the vertical displacement is given by

$$\zeta(x, z) = f(x)\phi(z), \tag{1}$$

where $\phi(z)$ satisfies the linear eigenvalue problem for long waves, *viz.*,

$$[\rho(U - c_0)^2\phi_z]_z + \rho N^2\phi = 0, \tag{2a}$$

subject to

$$\phi = 0 \quad \text{at} \quad z = 0, \tag{2b}$$

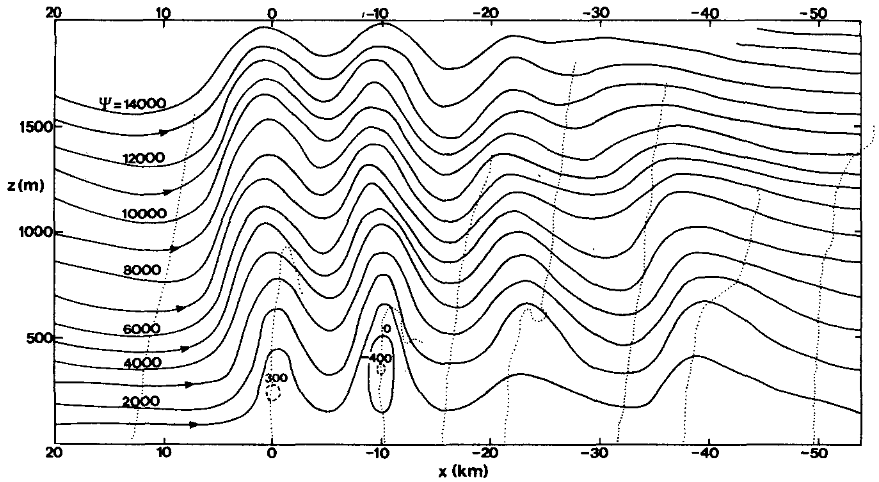

FIG. 13. Cross-section of the relative stream function $\phi(x, z) = -\int_0^z (u - c)dz$ for 4 October 79. Balloon trajectories are shown by dotted lines.

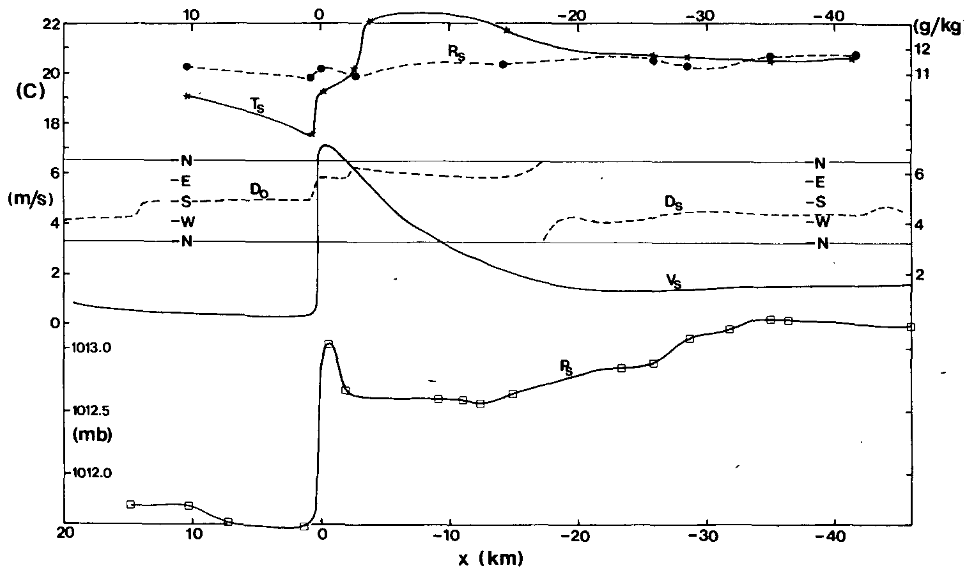

FIG. 14. Surface mixing ratio R_s, temperature T_s, wind direction D_s and speed V_s, and corrected pressure P_s, expressed in terms of distance from the leading edge of the morning glory, 29 September 1979.

and

$$\phi = 1, \quad \frac{\partial \phi}{\partial z} = 0 \quad \text{at} \quad z = h.$$[5]

In Eq. (2a), $N^2 = -gd\ln\rho/dz$ is the Brunt-Väisälä frequency in the lower layer and c_0 is the phase speed of infinitesimal long-wave modes. The function $f(x)$ in Eq. (1) satisfies a complicated equation, given in Appendix A, whose coefficients depend on the linear eigenvalue and eigenfunction of a particular mode.

The solitary wave solution for $f(x)$ is

$$f(x) = \frac{a\lambda^2}{x^2 + \lambda^2}, \tag{3}$$

which represents a symmetrical "hump" profile with amplitude a and half-width λ. The propagation speed c is greater than the infinitesimal phase speed c_0 by an amount which is an increasing function of wave amplitude, and it, together with both a and λ, depend on the details of the solution to the linearized eigenvalue problem as detailed in Appendix A. The corresponding solution in the layer above the inversion has the same form as Eq. (1), but with λ in Eq. (3) replaced by $\lambda + z - h$.

[5] The condition $\phi = 1$ normalizes the eigenfunction.

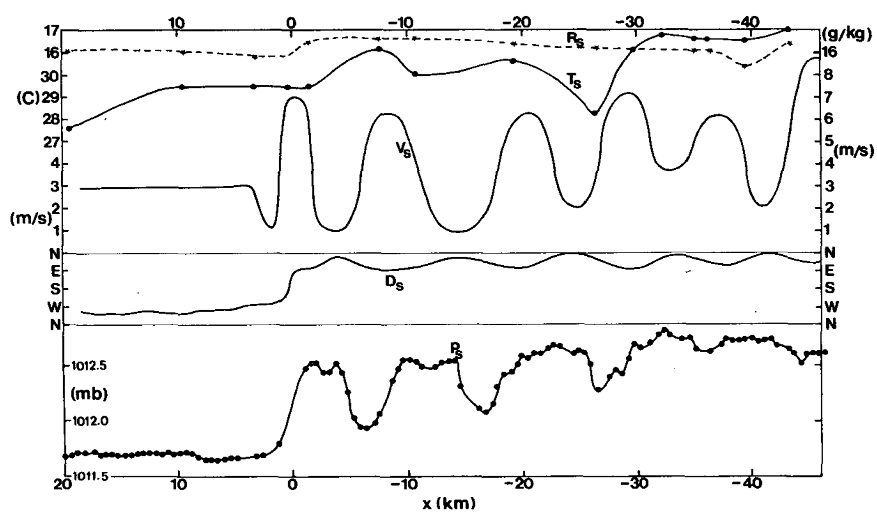

FIG. 15. As for Fig. 14, for 4 October 1979.

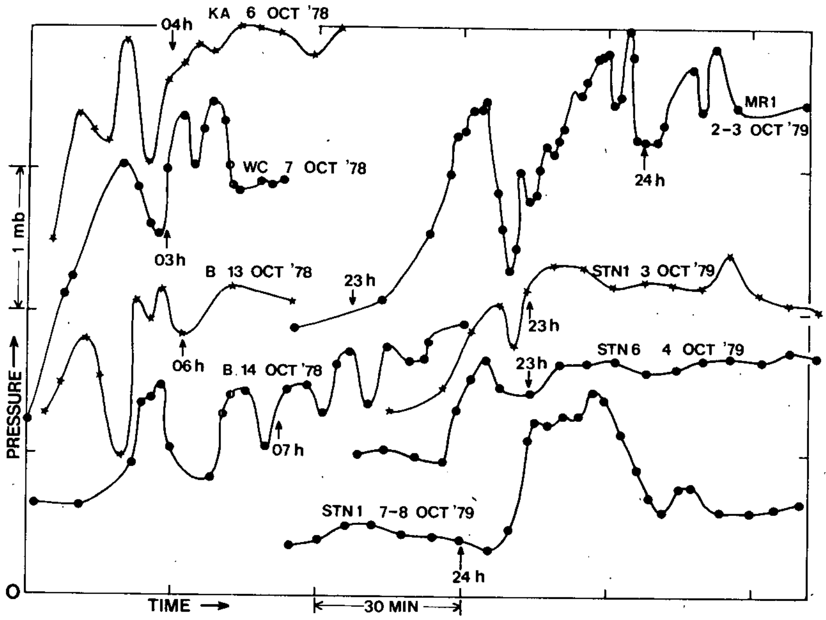

FIG. 16. Details of eight morning glory pressure jumps (corrected) observed in the Gulf area. The origins of abscissa and ordinate are arbitrary.

1) MORNING GLORY OF THE 29TH

The inversion layer ahead of the morning glory on the 29th has a depth h of 690 m and the Brunt-Väisälä period within the layer, $2\pi/N$, is well approximated by the constant value 5.9 min. The variation of density across the layer is of the order of 1% and can be ignored. The upstream wind profile is approximately linear through the layer and can be represented by

$$U = U_1 z h^{-1} - U_2,$$

where $U_1 = 8$ m s^{-1} and $U_2 = 1$ m s^{-1}, assuming x and U are positive in the direction of propagation of the disturbance with the coordinate axes x, z now fixed relative to the ground.

With these specifications, the linear eigenvalue problem [Eq. (2)] gives, for the gravest mode, a phase speed c_0 of 10 m s^{-1}, and for amplitude-to-depth ratios a/h of 0.2, 0.5 and 1.0, the solitary wave speeds as calculated from the Benjamin theory are 10.6, 11.4 and 12.5 m s^{-1}, with corresponding wave half-widths of 850, 340 and 170 m, respectively. The details of the calculation are sketched briefly in Appendix B. The observed translation speed of the morning glory on the 29th is 10.8 m s^{-1} and the half-width of the single wave leading the disturbance is estimated to be ~3 km.

In comparing theory with observation, it must be remembered that the Benjamin theory is derived on the assumption that $a/h \ll 1$, whereas the observed ratio a/h is of order unity. Nevertheless, the calculated speed of propagation, which within the confines of the theory is not overly sensitive to a/h, agrees well with the observed speed of translation. On the other hand, the calculated wave half-widths agree poorly with observation. However, unlike the phase speed, these are not only strongly dependent on a/h, but appear also to be sensitive to the details of the eigenvalue problem, and to higher order nonlinear effects (Grimshaw, 1981b).

2) MORNING GLORY OF THE 4TH

The inversion layer ahead of this disturbance has a depth of 630 m and, again, the Brunt-Väisälä period within the layer is nearly uniform with a value at about 0840 LST of 5.1 min. On this occasion, the

TABLE 1. Mean pressure changes, raw and corrected, 3 hours after a pressure jump.

Place	Mean time (LST)	Number of pressure jumps	$\delta_3 p$ (mb)	Number of negative jumps	$\delta_3 p_c$ (mb)	Number of negative jumps
Kowanyama	2135 ± 50 min	20	1.3 ± 0.5	0	1.3 ± 0.5	0
Normanton	0300 ± 90 min	52	2.2 ± 0.9	1	0.7 ± 0.6	5
Mornington Island	0630 ± 85 min	42	2.4 ± 0.9	0	0.9 ± 0.6	2

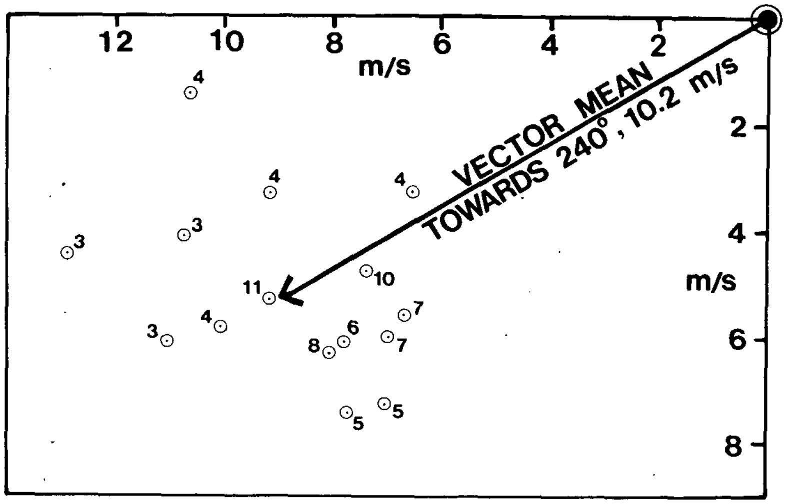

FIG. 17. The velocity vectors for fifteen pressure jumps as determined from times of passage at the number of stations shown. Some of these passages are based on wind changes, at places where no pressure was measured. The vector mean of the fifteen vectors is shown by the arrow.

wind speed for $z \leq h$ can be taken as approximately uniform with height with an average speed of 2.2 m s^{-1} opposing propagation (see Fig. 5). The morning glory on this day was accompanied by at least five waves and it seems appropriate to adopt the periodic solution of Benjamin, rather than that for the solitary wave, as a basis for the comparison of theory with observation. For this solution, $f(x)$ in Eq. (1) has the form

$$f(x) = \frac{\frac{1}{4}a \sinh^2 p}{\cosh^2(\frac{1}{2}p) - \cos^2(\pi x/L)}, \quad (4)$$

where a is the amplitude of the wave, $f_{\max} - f_{\min}$, L the wavelength, and p a constant which depends on a and L and on the details of the linear eigenvalue problem (see Appendix A). Again, the phase speed c exceeds c_0 for a particular mode, in this case by an amount which increases with both a/h and h/L [see Eqs. (A1)–(A8)]. The observed wavelength based on the separation of the leading wave crests is almost exactly 10 km giving a ratio $h/L = 0.06$.

For this situation, the linear eigenvalue problem gives a phase speed of 6.0 m s^{-1} for the gravest mode, and for ratios a/h equal to 0.2, 0.5 and 1.0, the total phase speed c takes values of 7.7, 8.4 and 9.7 m s^{-1}, respectively. Again, the observed ratio a/h is of order unity and the extent to which the theory is applicable is therefore uncertain. However, the calculated phase speeds are, as before, relatively insensitive to a/h and compare favorably with the observed translation speed of 9.0 m s^{-1}.

Despite the limitations of the theory, the foregoing calculations broadly support our identification of the morning glory as a propagating undular bore on the low-level nocturnal or maritime inversion. It is then clear why occurrences are confined to the morning, since the inversion, at least over land, is largely eliminated by midmorning as the daytime mixed layer becomes established.

Aside from the question of generation mechanisms, a number of fundamental problems have yet to be resolved. For example, while Benjamin's model assumes neutral stability above the inversion layer, the observed Brunt-Väisälä period in this region, certainly up to 2 km, is a mere 14 min, little more than twice that in the inversion itself. The degree to which this stability at upper levels assists the disturbance to propagate is difficult to determine, as is the amount of energy radiating upward. Indeed, it seems necessary to consider the possible existence of an upper level inversion above 2 km, the limit of our aircraft soundings, since this might substantially reflect upward radiating energy to give a trapped wave of greater vertical extent than the waves already considered. It turns out that the gravest wave mode in such a configuration has a linear phase speed out of line with the observed speeds, and since there is no evidence that the observed waves suffer a reversal of phase with height, the existence of higher modes can likewise be discounted.

Grimshaw (1981a) has generalized the BDO equation to take account of a weak stratification in the layer above the inversion allowing the e-folding decay rate of a solitary wave to be predicted. Application of this theory to the morning glory leads to estimated decay half-times of the order of a few minutes to an hour which is totally unrealistic (Grimshaw, personal communication). However, the calculated decay rate is proportional to both *a/h* and to the inverse cube of the Brunt-Väisälä period in the upper layer, which is required to be large compared with that in the lower layer. Hence the underestimate of decay half-times is not surprising and the problem of upward radiation remains unresolved.

A further question concerns the role of moist processes. Since not all pressure jumps recorded at the surface are associated with cloud, it may be surmised that moist processes are not crucial, but the extent to which they can energize the disturbance has yet to be determined.

It is perhaps worth noting that current theories are based on the assumption that all the streamlines in a disturbance originate in the flow far upstream, i.e., the solutions are invalid, at least locally, when there exist centers of closed circulation. Again, the extent to which this detracts from the comparisons made above is not known.

3. The morning glory: Conducive conditions and concomitant events

a. Examination of synoptic data

These were made available by the Bureau of Meteorology in the form of daily MSL weather maps, weekly barograph traces from Mornington Island and Normanton, with partial barograph data from Kowanyana; standard three hourly observations from Normanton and Cairns, and six hourly upper wind observations from the latter. The Bureau observer at Mornington Island recorded morning glory occurrences there during the expedition and also photographed several.

In an attempt to determine conditions favorable to morning glory formation, we have examined available data for late September and October, 1976–79, searching for possible determinants for pressure jumps at Normanton. These studies include upper winds (500 m) at Cairns (no other routine aerological soundings nearer than Mount Isa are made), surface pressure differences between Cairns and Thursday Island and Cairns and Normanton, surface temperatures, dew points and winds. Westerly upper wind components, or easterly components above 6 m s^{-1} at 2100 LST, are not conducive to pressure jump occurrences at Normanton the following morning, nor are surface winds with a southerly component at Normanton.

The best two parameters we have found for separating pressure jump days at Normanton from those without appear to be the dew point at Normanton and the pressure difference between Cairns and Normanton, a measure of the southward component of geostrophic wind. Fig. 18 is a scatter diagram

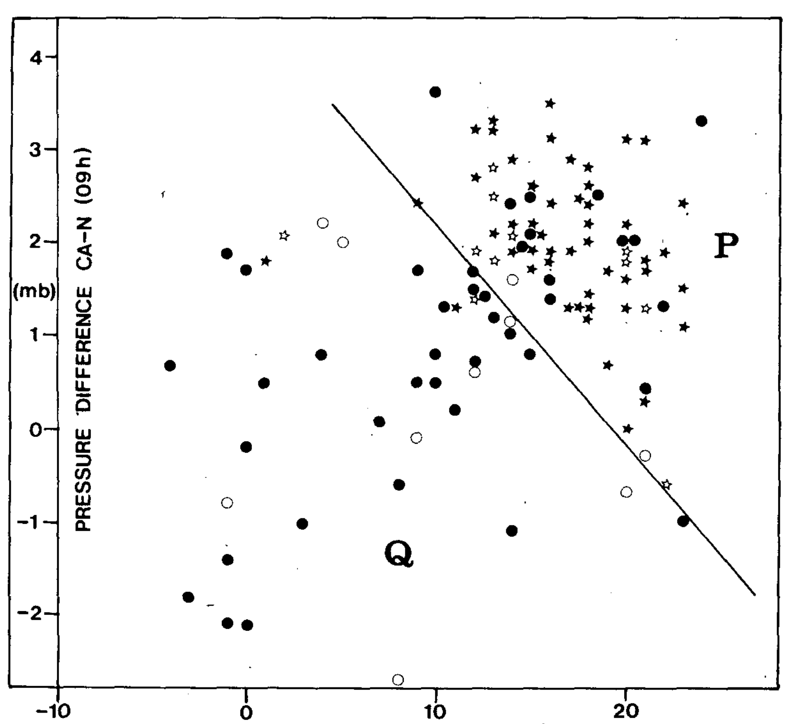

FIG. 18. Scatter diagram showing days with (stars) and without (circles) pressure jumps at Normanton. Hollow symbols refer to doubtful cases. The line separates the diagram into two parts, *P* and *Q*, in which jumps respectively do and do not commonly occur.

TABLE 2. Details of pressure jumps occurring at Mornington Island (M) and Normanton (N), from weekly barographs.

		Number of cases
Mean time at N (LST)	0305 ± 100 min	62
Mean time at M (LST)	0635 ± 85 min	60
Mean difference in time	3 h 25 min ± 80 min	45
Percent frequency at N	56	111
Percent frequency at M	61	99
Number of jumps at both M and N	45	99
Number of jumps at N and not M	10	99
Number of jumps at M and not N	15	99
Number of days with no jumps at M and N	29	99

with these variables as axes. Of a total of 111 days, 62 had pressure jumps, although it is unlikely that all were accompanied by cloud. In the area on Fig. 18 marked P, 81% had pressure jumps and in Q only 10%. Thus it is rare for a jump to occur with a dew point below 12°C, and not to occur with one above 20°C, while a pressure difference of at least a millibar appears to favor pressure jump formation.

To provide a check on the cohesiveness of the pressure jump lines, a listing also was made of pressure jumps occurring at Mornington Island. Table 2 summarizes the results. Only one pressure jump was listed per day, although two, separated by minutes or an hour or so, may occur. The time difference between the jump at Mornington Island and that at Normanton ranges from −30 min (the only negative value, with both jumps classed as doubtful) to 5 h 40 min. It is clear from Table 2 that jumps usually occur at both stations (45 out of 70 jump days) and there is strong evidence that the majority of paired jumps correspond with the same disturbance. Indeed, on most of the 45 paired jump occasions, the times of passage at Normanton and Mornington Island are consistent with a jump line moving forward in the direction of about 240° at a speed of $\sim$10 m s^{-1} and the jumps of a pair are similar in structure at the two places.

Long-term, seven times daily pressures are available from Bureau of Meteorology stations Brisbane, Cairns, Canberra, Charleville, Cloncurry, Longreach, Mackay, Normanton, Townsville, Sydney and Wagga Wagga, marked on Fig. 2. The driving force for the strong continental-scale sea breeze is the diurnally varying pressure gradient between the coast and places inland, a manifestation of what Wagner (1938) called "the breathing of the continent." The sea breeze frequency and vigor are expected to be related to the intensity of the diurnally varying gradient. Since mainly clear skies prevail in Queensland during October, except along the coast, the frequency of sea breezes is very high and variations in the coast-hinterland pressure gradient largely reflect the intensity of the mean solar heating and nocturnal cooling over the land.

The diurnal amplitude and phase of the mean surface pressure difference δp between the coast and places well inland is shown in Table 3. The amplitude of the Cairns-Normanton δp variation suggests that, as far as the continental-scale sea breeze mechanism is concerned, the southern Gulf coast is a part of the interior, and that east coast sea breeze penetration and intensity should be at least as pronounced (or more so because of smaller coriolis turning) in October as it is further south. Not much is known about such penetrations there, but at Canberra (elevation 565 m) there is a considerable frequency of summer sea breezes, arriving between 1600 and 2000 LST, and some of these are detected in some form at Wagga Wagga. A high-pressure ridge along the coast is well known to be a precursor of such events. Similar sea breezes occur at Toowoomba (100 km inland, latitude 27.5°S).

The prevailing geostrophic wind along the coast near Cairns in October is onshore, and the high-pressure ridge is frequently present, as implied by the Cairns-Normanton pressure differences in Fig. 18. A synoptic-scale onshore wind is known to assist the inland penetration of sea breezes, although tending to make their fronts diffuse. With too strong an onshore geostrophic wind, the sea breeze front may be inhibited or masked. Evidence that the east coast sea breeze penetrates much further inland than

TABLE 3. Range and phase of mean pressure differences between stations on the east coast of Australia and those inland.

Station pair			Distance from east coast (km)		Latitude (°S)				
(1)		(2)	(1)	(2)	(1)	(2)	Month	Range of δp (mb)	Time of maximum δp (LST)
S	—	C	~0	115	33.9	35.3	Jan	1.4	1500
S	—	W	~0	265	33.9	35.1	Jan	1.6	1800–2100
BR	—	CHA	~0	570	27.5	26.4	Oct	1.6	2100
MA	—	L	~0	540	21.1	23.4	Oct	1.6	1800–2100
T	—	CL	~0	620	19.3	20.7	Oct	1.6	1800–2100
CA	—	N	~0	485	16.9	17.7	Oct	1.9	2100

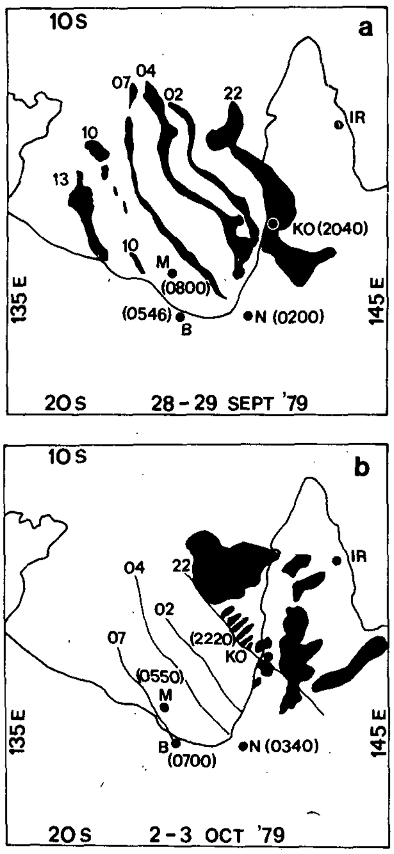

FIG. 19. (a) Representation of cloud lines on 28–29 September 1979, at 2200, 0200, 0400, 0700, 1000 and 1300 LST with times of pressure jumps at Kowanyama, Normanton, Burketown and Mornington Island. The lines are from GMS infra-red imagery. (b) The location of cloud lines on 3 October 1979, from 0200 to 0700 LST, with times of passage of pressure jumps as in (a). Cloud at 2200 LST on 2 October 1979 is also shown over the Peninsula and Gulf.

that for the west coast one on the Peninsula is frequently to be seen on afternoon GMS visual imagery, when the cumulus-free margin indicative of the sea breeze, inland of the east coast, is normally several times wider than that of the west coast.

b. Satellite imagery

The DMSP orbiting satellite imagery, both visual and infrared, for the period 23 September–10 October was obtained from the University of Wisconsin. Similar three hourly imagery from the Japanese Geostationary Meteorological Satellite (GMS) stationed at longitude 140°E, was supplied by the Australian Bureau of Meteorology.

Neal and Butterworth (1973) and Neal *et al.* (1977c) address the problem of recurring cloud lines in the Gulf as seen in satellite imagery, and have found the evidence to be ". . . inconclusive. A surface pressure jump is not always associated with a morning glory; the morning glory does not coincide with the cloud line." These conclusions are not disputed, but it is evident that the same processes which produce the morning glory are also at work in producing the cloud lines. At least some lines originate on the Peninsula about the same time of day as the morning glory and move toward the west-southwest with comparable speeds. Since the morning glory is associated with, at most, a narrow line of cloud, no more than a few kilometers wide, and since the best available satellite data gave a resolution of ~3 km in the visual band and 7 km in the infrared, lines thin enough to be a single glory line are not likely to be often seen. We concur with Neal *et al.* (1977c) that winter cloud lines in the northern Gulf, where the dry continental air does not often penetrate, are probably associated with morning glories which are not made manifest further south.

The progression of cloud lines as seen in the GMS infrared imagery on the 28–29th and 2–3rd is shown in Fig. 19. The imagery on the 29th (Fig. 19a) at 0200 and 0400 LST shows cloud lines typical of many such lines seen at these hours, the forward bowing about latitude 14°S apparently being a positive response to the higher ground in the Dividing Range near Iron Range. Times of passage of pressure jumps at Kowanyama, Normanton and Burketown in Fig. 19a bear no relation to these satellite observed cloud lines, which the enhanced imagery at 0400 shows to have a cloud top temperature near 0°C, corresponding to a height above 4 km. By 1600 only a few scattered remnants of this cloud line remain. A speed of 10.8 m s^{-1} between 0200 and 1000 is derived from this sequence and the passage at Mornington Island occurred at about the same time as the pressure jump on that day. Moreover, this speed is precisely that determined from the pressure jump data, but the cloud line around the south east corner of the Gulf lagged the pressure jumps by 4–5 h!

On the 2–3rd (Fig. 19b) the cloud line is evidently in step with the pressure jump at all four stations, although irregularity is exhibited near Kowanyama in the formative stages; station 1 shows a clear pressure jump at 2235 LST, and detailed observations from Mitchell River site 1 (Fig. 2) show an intense pressure jump at 2306, with large cumulus clouds and a rain shower to the east, the first rain for many months. No cloud came over Mitchell River site 1 and the cloud mass to the east dissipated very rapidly after the passage of the pressure jump there. These observations suggest that the pressure jump line observed later, at places further west, was an amalgam of several discrete arcs emerging from the cumulus mass detected in the infrared imagery at 2200, where a rough line was already in evidence. The height of cloud tops according to the enhanced imagery again is near 4 km. At 1000 and 1600 on the

3rd (not shown in Fig. 19b), thin cloud lines, knotted with cumulus clumps, at first sight suggesting morning glory lines, are in evidence in the central Gulf, rearward of the depicted 0700 line, and nearly stationary.

The apparent separation of a shallow morning glory line from a deep cumulus line is well illustrated by the sequence on the 3–4th. At 2200 LST on the 3rd, a broad deep cloud band lay NNW–SSE, centered some 75 km east of Kowanyama. At 0200 and 0400, the cloud had spread chaotically over much of the Gulf. No clear cloud line was visible at 0700, except a NNW oriented line appearing in the extreme southeast corner of the Gulf. This remains nearly stationary on the 0817 and 1054 DMSP visual imagery (Fig. 20) and has "frayed" into a wavelike pattern over the land to the south. By the later time, the morning glory of the 4th with its 5-wave train has passed Burketown having left behind a cloud line with tops to ~5 km, itself having tops to only 2.5 km, and appearing as a 150 km long blurred line in the expected position west of Burketown.

In October the prevailing easterly winds over the Gulf almost certainly decrease with height above about 1 km; at Cairns the mean decrease is ~3 m s^{-1} km^{-1} between 1 and 3 km. Thus deep convective clouds would be expected to move only slowly from the east. Potential instability over the Gulf is probably of frequent occurrence. The passage of a morning glory, with its marked lifting, would be expected on occasion to trigger deep convection, which might persist for some hours, drifting with the mean wind, while the morning glory, essentially a wave, continues on its way, its velocity being determined by the structure of the maritime boundary layer and its own amplitude. It seems likely that the interaction of the glory and convective processes positively affects both. The convulsion produced by the waves promotes convection, but the waves themselves appear to be strengthened by moist processes. There is thus much difficulty in interpreting satellite imagery, which represents the result of this ever-changing interaction.

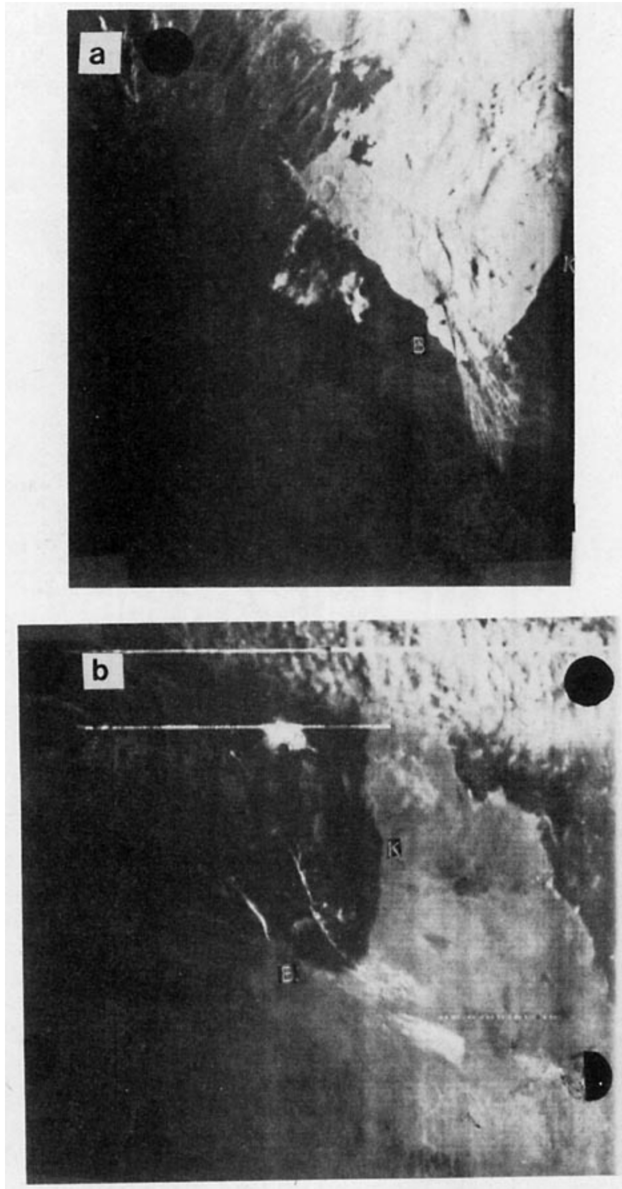

FIG. 20. DMSP satellite imagery for the Gulf of Carpentaria on 4 October 1979; (a) 0817 LST, (b) 1054 LST. Burketown (B) and Kowanyama (K) are marked.

c. The Cape York observations

The Cape York Peninsula has a backbone of hills in the east, bordering the Pacific Ocean, but a little west of the town of Chillagoe it becomes a gently sloping alluvial plain extending 300 km to the Gulf of Carpentaria. The plain is covered by eucalypt forest, generally not exceeding 10 m in height, with seasonal growth of grass in the wet season, November/December to April/May. The only road giving access westward across the Peninsula even vaguely normal to the morning glory orientation is a rough and extremely dusty "cattle-train" earth road, trafficable only by four-wheel drive vehicles and impassable when wet, between the Aboriginal settlement at Kowanyama and the railhead near Chillagoe, a distance of 422 km (Fig. 2). For morning glory studies, the road orientation leaves much to be desired.

In an effort to determine the region and mechanism of morning glory genesis, a number of recording digital barometers and Woelfle anemometers were stationed along this road [the barometers at stations 1 and 6 and anemometers at stations 1, 3, 5, 7 and 11 (see Fig. 2)] and were maintained for the period 23 September–10 October by two expedition members. These persons also continuously

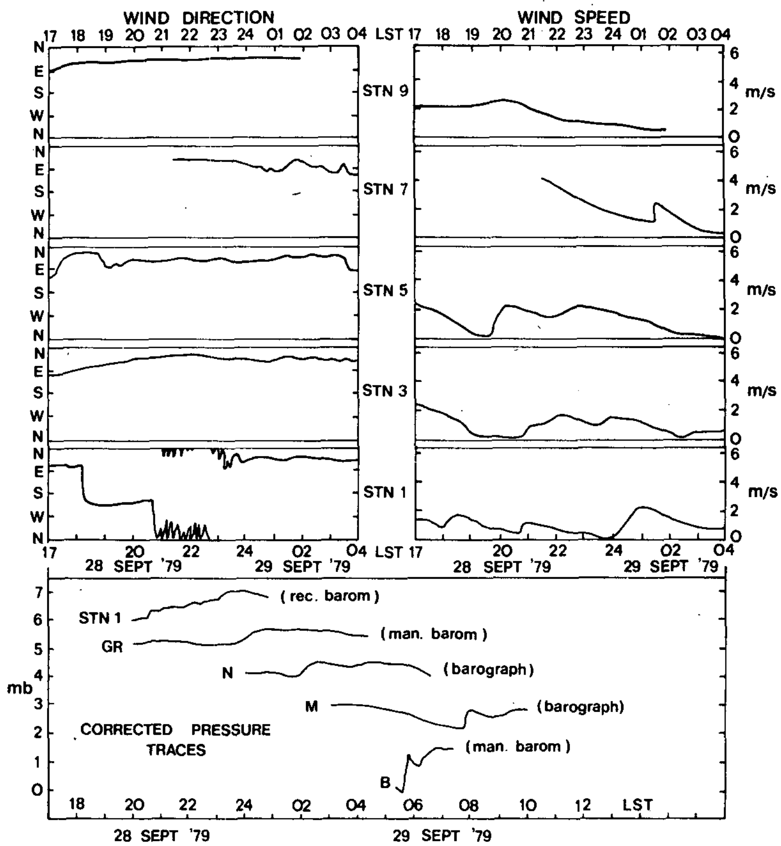

FIG. 21. Wind speed and direction from 1700 LST to 0400 LST on 28–29 September 1979 at stations 1, 3, 5, 7, 9, and corrected pressure signatures at station 1, Gilbert River, Normanton, Mornington Island and Burketown.

observed cloud, wind and pressure, looking for signs of morning glories, and kept frequent records. A malfunction of the anemometer at station 9 necessitated its replacement by the instrument at station 11 after only five days operation. Other sites, such as Chillagoe, Gilbert River, Karumba, Lynd River, Mitchell River (sites 1 and 2) and Walker Creek, were manned occasionally in 1978 and 1979. Detailed results are presented only for the two cases investigated at Burketown, *viz.*, the 28–29th and the 3–4th. Data for other days are summarized briefly.

Figs. 21 and 22 give the wind speed and direction and the corrected pressure traces available for the 28–29th and the 3–4th. Barographs and digital aneroid barometers, both manual and recording, are the source of the pressure data. The wind was recorded at 2 m above the ground, in relatively open parts of the tree-covered plain, and thus speeds are not representative of those above the canopy. However, a major part of the interest lies in the direction traces. The best exposed site was station 7, where "regrowth" was only 1–3 m high in an extensive cleared area. Regrettably, the instrument located there only recorded satisfactorily during the cooler night hours.

1) THE 28–29TH

The east wind blew all night with decreasing strength at stations 9 and 7; at station 5 a daytime east-northeast wind decreased to calm by 1900 LST, but sprang up again as a very gusty east-northeast breeze about 1940. At station 3 the calm period lasted until nearly 2100, while at station 1 the southwest sea breeze from the Gulf blew from 1820 to 2040, before giving way, with a minor pressure jump, to an oscillating northerly wind which persisted until the northeast breeze arrived about midnight, with no pressure signature. The small pressure jump appears also at Gilbert River and Normanton, and, on the grounds of continuity, this appears to have reached Burketown in the much amplified form of the morning glory at 0546. The pressure jump at Mornington Island does not fit the hypothesis of continuity with those at the other stations, and has been identified with the passage of the major cloud line (Fig. 19a). The propagation velocity assessed

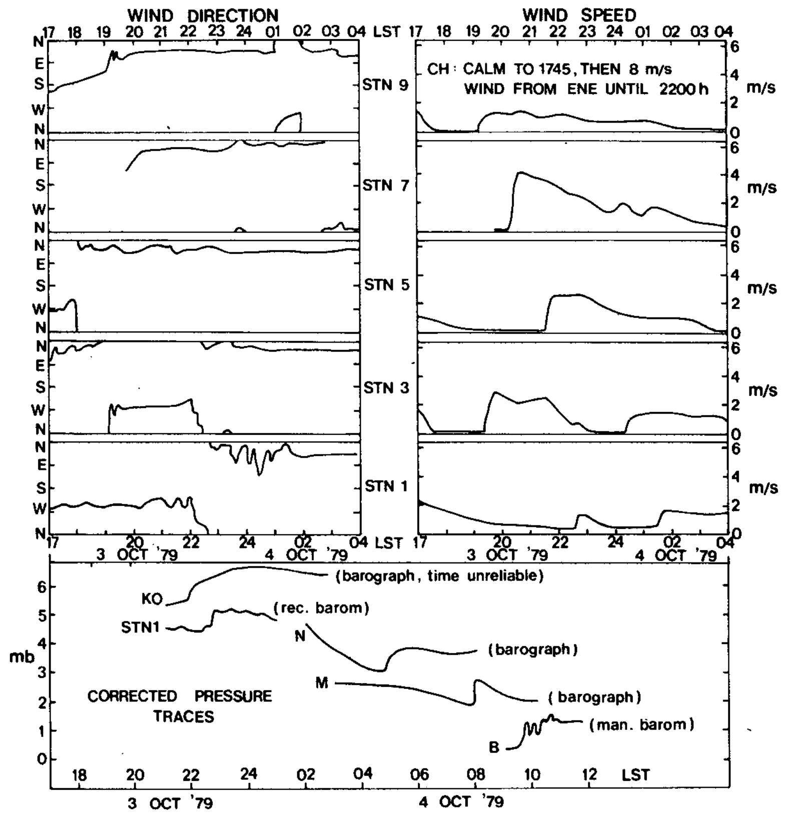

FIG. 22. As for Fig. 21, for 3–4 October 1979.

from passages at station 1, Gilbert River, Normanton and Burketown is toward 224° at 10.8 m s^{-1}, while the observation at Burketown gave it a speed of 10.6 m s^{-1} toward 220°, in excellent agreement.

2) THE 3–4TH

At Chillagoe a strong gusty east-northeast wind replaced a calm at 1750 (a common occurrence according to local inhabitants) and blew well into the evening; at station 9 it arrived at 1910 and blew with diminishing force until 0100; at station 7 it arrived about 2020, at station 5 at 2130, at station 3 a west-southwest breeze fell to near calm about 2230 and the northeasterly surge arrived about 0025; at station 1 the southwest sea breeze gradually expired and was replaced at 2235 by a minor wind maximum from the north-northeast, accompanied by a 0.8 mb pressure jump. The steady northeasterly wind arrived about 0130. The progress of the pressure jump to Normanton, Burketown and Mornington Island agrees reasonably well with the hypothesis that it was a straight line moving toward 237° at 9 m s^{-1}. It should be stressed that at station 1 the pressure jump, if it was originally related to the onset of the northeast wind, appears to have run on ahead of the decelerating northeast surge by some 3 h, and there is some evidence that this is also the case at station 3, where the time lag is <2 h. No such feature is suggested by the wind traces at the other anemometer stations.

d. Comments on the data for other expedition days

It is worth noting that a strikingly similar sequence to that on 3–4th occurred on the previous evening, 2–3rd. On this occasion the westerly sea breeze at station 3 gave way at 2230 LST to a light, fluctuating northerly wind, which, 2 h later was replaced by a much stronger northeasterly; at station 1 the westerly sea breeze had expired before it was replaced at 2235 by an oscillating north to east wind, with a pressure jump of 1.0 mb. Some 3 h 50 min later the steady northeasterly wind arrived without a pressure jump.

Since synoptic data over at least this part of the Peninsula are virtually non-existent, the expedition surface data are unique. They are summarized below, for the period 24 September to 10 October, 1979.

The period 24–28th was characterized by unusually strong easterly winds on the Peninsula, according to local graziers. No morning glories were reported, although a pressure jump occurred at Mornington Island on the 25th. The surface easterlies were interrupted by a westerly sea breeze only at station 1, and dew points were generally low. Satellite imagery revealed cloud line sequences on the 25th, 27th and 28th over the Gulf, moving west-southwest at speeds of 9.4, 7.9 and 8.4 m s^{-1}, respectively, similar to those in Fig. 19a. These probably represent morning glories over the Gulf, but we have no supporting evidence.

On the evening of the 29th a frontal cloud band and wind change from north to southwest moved over the Gulf from the south, and dew points fell to very low values on the 30th, 1st and 2nd. No morning glories were observed on these days.

On the 2–3rd and 3–4th the surface humidity rose, geostrophic wind became northerly over the Gulf and morning glories were observed.

By the 4–5th geostrophic west-northwest winds, uncommon in October, had become established over the southern Gulf, ahead of a frontal trough 700 km to the southwest, and humidities became very high. There is no easterly surge across the Peninsula. Instead, what is probably a weak north to northeast drainage flow occurs at night and replaces the westerly wind at station 5, 3 and 1 at 2305, 0005 and 0010 LST, respectively, accompanied by a marked oscillation in wind direction with a period of ~15 min persisting for 1.5–2 h at all stations, and a pressure jump of 0.6 mb at stations 1 and 6. A pressure jump of 0.8 mb was observed at Normanton at 0700, and a narrow cloud line extended northwest from there across the Gulf. No morning glory or pressure jump occurred at Mornington Island or Burketown, where the westerly winds were strong in low levels and about 1500 m deep.

At 0700 LST on the 6th, visual satellite imagery showed two narrow cloud lines, resembling a morning glory, moving over Burketown from 190°, in the axis of a moving frontal trough, and dew points fell to low values over the southern Gulf, behind the trough line, on the 6th, 7th and 8th. Over the central Peninsula humidity remained high on the 5–6th and drainage winds from the north-northeast again appeared, replacing the westerly sea breeze, with attendant 15 min oscillations and a 0.5 mb pressure jump at station 6.

On the night of 7–8th a short-lived wind and pressure pulse moved through the line of instruments from station 9 at 2120 to station 1 at 0005, its duration at each station being roughly half an hour. Its pressure signature is shown in Fig. 16. A similar pulse occurs at Normanton at 0540 and a slight response at Mornington Island at 0800, but no morning glory was observed there. At Mitchell River (site 2) its passage was visually observed at 2320, where the northeasterly wind rose to 5 m s^{-1} and a very thin line of cloud moved from the east-northeast at a height estimated at 800 m. A speed of 10.2 m s^{-1} towards 232° was estimated from the pressure jump data. This event differed from those on the 29th, 3rd and 4th in that no *sustained* northeasterly wind spread across the Peninsula.

On the remaining days, 8–9th and 9–10th, humidity was high and geostrophic winds were northerly. The instrument array was being dismantled, starting from station 1. The 9–10th fits fairly well into the pattern set by the 2–3rd and 3–4th, but on the 8–9th the duration of the northeast surge was only an hour or so at stations 5, 7 and 9, somewhat similar to the 7–8th. On the 9th and 10th marked pressure jumps occurred at Normanton and at Mornington Island, where the pressure jump on both days was double, separated by 10 and 50 min, respectively, and a morning glory was noted at the first pressure jump by the Bureau of Meteorology observer at Mornington Island.

4. Origin of the morning glory

a. The east or northeast wind surge on the western side of the Peninsula

This surge is, as we have seen, traceable all the way westward from at least Chillagoe, and its leading edge is frequently, in a sense, continuous in time with the gust front of the glory. It is presumably the onset of this gust and its following easterly wind which led the Royal Australian Air Force (1942), erroneously, to identify the glory, as observed at Karumba, as a "land breeze".

It is difficult to acquire definitive data in the area of genesis, both because of its inaccessibility and because disturbances there are unmarked by cloud, but Maxworthy's remark (see earlier) concerning the ubiquity of solitary wave disturbances in flow configurations which support them raises the possibility that there exist several distinct genetic mechanisms. We have evidence that this is the case in the atmosphere (see later).

The northeast or east wind surge across the Peninsula occurs on all the five days of known morning glories during the 1979 expedition. It did not occur on the 4–5th and 5–6th, when westerly geostrophic wind prevailed, and the east coast was in a lee pressure trough. Despite this, a light north-northeast, presumably drainage, flow ushered in by a pressure jump on the Peninsula did occur on these nights and, although no glory resulted at any observing station, one may well have been present over the Gulf, where a cloud line was observed in satellite imagery. On the days when there were no pressure jumps, the easterly wind did not surge, but was present all night.

b. The role of vertical wind shear

Out of 16 days of surface wind records obtained at Burketown during the 1978 and 1979 expeditions, 10 showed early morning easterly or southeasterly winds and on these, no morning glories occurred. Strong, deep northwesterly winds up to ~1500 m were recorded on the 5th and no morning glory occurred on that day either. On the remaining five days when morning glories occurred, light winds from the sector south to west were observed in the early morning. This suggests that low-level opposing winds are conducive to the maintenance of morning glories (see Figs. 4 and 5). Support for this idea comes also from the report of Neal *et al.* (1977b) which presents "average surface winds" at Karumba for "all days", "southeasterly wind days", "pressure jump days" and "northeasterly wind days". It is only on pressure jump days that mean wind directions are from the west (~260°, apparently a sea breeze remnant) between 0000 and 0300 LST, i.e., prior to the arrival of a pressure jump. The other categories all have southeasterly winds during these hours. The mean upper wind of Neal *et al.* on pressure jump days at 0200 suggest the westerly component is 300–400 m deep. One possibility suggested by these data is that by enhancing flow relative to the internal bore, opposing winds in the inversion layer act to keep the upstream flow supercritical with respect to the surge which initiates and maintains the bore.

c. Possible mechanisms

The known facts are consistent with at least four mechanisms for the production of a pressure jump:

1) The continental sea breeze front surges across the Peninsula on many days, except when the geostrophic wind is westerly, or when the easterly geostrophic wind is too strong. The speed of this front is similar to that of the glory, 8–10 m s^{-1}. From about station 9 (163 km from the east coast), or earlier, it propagates through a developing nocturnal inversion. The interaction of the sea breeze gravity current with the inversion is probably the principal genetic mechanism for the pressure jumps observed on the west coast of the Peninsula. Simpson *et al.* (1977) have described the production of a horizontal vortex from a sea breeze in southern England at 1700–1800 local time, when the inversion is incipient. Similar cutoff vortices, remnants of sea breeze fronts, were observed on several occasions 160 km inland at 2100–2200 LST in 1961 during the Coonalpyn Downs expedition (Clarke, 1965), although the information obtained on them was fragmentary.

The sequence of events at stations 1 and 3 on the 2–3rd and 3–4th, with two wind changes, the first accompanied by a pressure jump, is reminiscent of experiments performed by Maxworthy (1980). On releasing dyed heavy fluid into a stably stratified environment he observes (p. 55) that as the front evolves ". . . it is embedded in a large amplitude solitary wave. The front . . . is composed of dyed fluid. . . . As the wave evolves and its amplitude decreases the dyed fluid is ejected rearward. . . ." The wave front was observed to move ahead of the front of the main body of dyed fluid representing the principal density contrast, and to gradually evolve to a pure wave by ejection of dyed fluid, as its amplitude decreased. Maxworthy observed up to 12 waves, depending primarily on the initial potential energy of the released denser fluid. A difference between our observations and his experiment is that whereas his gravity current abruptly ceases propagating when the leading solitary wave separates from the base of the mixed fluid, our sea breeze continues to propagate, but at a reducing speed. The picture is further complicated in nature by the possible occurrence (as on the 2–3rd) of moist processes as a result of the sudden lifting by the advancing wave. These processes may act to enhance the disturbance.

2) The production of an internal bore on a katabatic flow is undoubtedly an important mechanism and appears to account for the pressure jumps on the 4–5th and 5–6th. The mechanism is probably less effective than 1), but might be assisted by moist processes.

3) Lee waves or standing eddies in the vicinity of high ground could collapse as a result of changing wind or thermal structure and, like Maxworthy's cylinder of mixed fluid, produce a gravity current and a series of internal waves. This could conceivably have been the mechanism on the 7–8th, when a sustained sea breeze did not occur, but a short-lived pulse propagated westward from station 9.

4) The head-on approach of a sea breeze from the east toward one from the west could result in a marked elevation of the stable region between, which, collapsing into the expiring westerly wind regime could initiate the formation of a disturbance with a pressure jump and, ultimately, solitary waves. The role of the westerly wind may, however, be more subtle.

5. Summary and conclusions

On the basis of a detailed investigation of two morning glories, it is concluded that the phenomenon, in essence, is an internal undular bore propagating on the shallow nocturnal boundary layer which has a depth of order half a kilometer. An analysis of other data shows that its occurrence is favored by high humidity at the surface, a pressure ridge along the east coast of North Queensland and a geostrophic northerly wind over the Gulf, which tends to increase humidity by advection. However, the role of moist processes is yet to be determined.

The apparent rolling motion in the clouds which often accompany the disturbance is a result of condensation at the leading edge of an approaching wave, followed by reevaporation at the trailing edge as the wave passes. The wave, or waves, which constitute the disturbance may be regarded as evolving solitary waves which, in the course of time, become organized into an amplitude ordered train, each with its surface pressure wave and, if the low-level moisture and wave amplitude are sufficient, its own cloud roll. Waves may be of large amplitude—comparable with the inversion depth—and a closed circulation may exist in these; however, such circulations involve a relatively small volume of fluid participating in the disturbance.

The disturbance, complete with pressure jump, generally originates over Cape York Peninsula, especially on the western side, and appears mostly to be the product of interaction between a sea breeze front from the east coast of the Peninsula and a developing nocturnal inversion. It is of frequent occurrence along the Gulf coast in October. What apparently distinguishes this area from others in respect to such processes is the frequent presence of fairly high humidity in a shallow surface layer, an opposing westerly sea breeze, strong nocturnal cooling at the end of the dry season, strong daytime heating, and low Coriolis parameter. The relative importance of the Dividing Range, 300–500 m high, near the east coast of the Peninsula cannot, as yet, be assessed, but it is known that high ground near a coast does not invariably hinder sea breeze activity, and does provide evening assistance to the sea breeze through downslope katabatic effects. Even in the absence of a sea breeze, model studies (Clarke, 1972) suggest that katabatic flow on the western slope of the Peninsula is capable of generating a pressure jump, and they show that the effect of reduced Coriolis parameter on the pressure jump is considerable. The importance of the westerly sea breeze is not known, but it may play a supportive role. Over the open Gulf the wind appears to remain northeast or east both before and after the passage of the glory.

The evidence suggests that surface winds accompanying the morning glory over the Gulf may temporarily equal, or slightly exceed, its speed of translation, typically 10.0 ± 1.5 m s^{-1}, and the vertical wind components at an altitude of 0.5–1 km may be of the same order, but without severe turbulence. The phenomenon is therefore a potential hazard to low-flying aircraft.

The implications of this work for understanding other, more violent tropical diurnal squalls have yet to be evaluated. Among these may be listed the Guba of the Gulf of Papua (Royal Australian Air Force, 1942, Part 3, p. 28), the Sumatra of the Strait of Malacca (McIntosh, 1963) and perhaps the Tehuantepecer (Parmenter, 1970). A cloud line similar to the morning glory sometimes appears in GMS imagery off the northwest Australian coast; this seems to have its origin at or near the Kimberley Plateau (17°S, 125°E) and propagates far to the west over the Indian Ocean.

The present study is necessarily incomplete; more glories must be analyzed and described, and their dynamic and thermodynamic structure explored in depth, before we can claim to understand the phenomenon completely. There remain also many unanswered questions about their genesis and some of the ideas presented here are speculative at this stage. Indeed, the detailed processes involved in producing an internal bore and solitary waves by the interaction of a gravity current with a stratified fluid environment are not fully understood. Nevertheless, the theory of finite-amplitude internal waves in deep fluids, including solitary waves, continues to develop rapidly and even now, quantitative answers can be given to certain questions.

More detailed observational work obviously is necessary to study the life cycle of the morning glory in its natural habitat, the Gulf, and to determine its relationship, if any, with the pressure waves which are detected at Tennant Creek, some seven hundred kilometers away.

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Finally, we acknowledge several helpful discussions about this work with Dr. Roger Grimshaw of Melbourne University and Mr. Doug Christie of the Australian National University in Canberra. Dr. Grimshaw also was kind enough to provide us with details of some of his unpublished calculations.

APPENDIX A

Periodic and Solitary Wave Profiles

The function $f(x)$ in Eq. (1) satisfies the equation

$$Af - Bf^2 + \mathscr{F}(f) = 0, \tag{A1}$$

where A and B are constants which depend on the solution of the linear eigenvalue problem, Eqs. (2), i.e.,

$$A = \frac{c^2 - c_0^2}{c_0^2} A^*, \tag{A2}$$

$$B = \frac{3}{2\rho(h)} \int_0^h \rho\left(1 - \frac{U}{c_0}\right)^2 \phi_z^3 dz, \tag{A3}$$

where

$$A^* = \frac{1}{\rho(h)} \int_0^h \rho\left(1 - \frac{U}{c_0}\right)\phi_z^2 dz, \tag{A4}$$

and $\mathscr{F}$ is an operator defined by

$$\mathscr{F}(k) = \int_{-\infty}^{\infty} |k|\tilde{f}(k)e^{-ikx}dk, \tag{A5}$$

where $\tilde{f}(k)$ is the Fourier transform of $f(x)$. Eq. (A1) is identical with Eq. (3.51) of Benjamin (1967), except for notation, and Eqs. (A2) and (A3) reduce to Benjamin's Eqs. (3.52) and (3.53) in the special case where $U(z) \equiv 0$.

The solitary wave solution given by Eq. (3) satisfies Eq. (A1) if

$$a = 2A/B \tag{A6}$$

and

$$\lambda = 1/A \tag{A7}$$

[see Benjamin (1967), Eqs. (3.79)]. Then (A2) and (A5) give

$$c = c_0\left[1 + \mu\left(\frac{a}{h}\right)\right]^{1/2}, \tag{A8}$$

where $\mu = \frac{1}{2}hB/A^*$ is a constant. Eq. (A8) gives the speed of propagation of a particular wave mode as a function of the linear phase speed and the wave amplitude. Also, the elimination of A between (A6) and (A7) gives a formula for the wave half-width as a function of wave amplitude, showing that $\lambda \propto a^{-1}$.

For the gravest mode, $\phi(z)$ increases monotonically with z through the inversion layer (i.e., $\phi_z > 0$) and reaches a maximum $[\phi_z(h) = 0]$ at the top of the layer. Thus B is always positive and, if $U \equiv 0$, A^* is positive also, so that $c > c_0$; i.e., the wave is *supercritical*. If $U \not\equiv 0$, the mode is supercritical provided A^* is positive.

The periodic wave solution given by Eq. (4) satisfies Eq.(A1) if $\sinh p = 4\pi/BL$, and if

$$c = c_0\left\{1 + \mu\left[\left(\frac{a}{h}\right)^2 + \left(\frac{4\pi h}{BL}\right)^2\right]^{1/2}\right\}^{1/2}, \tag{A8}$$

which reduces to Eq. (A8) as $h/L \to \infty$; the solitary wave limit. The typical shape of the periodic wave solution is shown in Fig. 4 of Benjamin (1967); significantly, the waves are sharply peaked and there is a mean upward displacement of the inversion from its undisturbed level. This is consistent with the existence of an increase in pressure following the passage of an undular bore composed of these wave types. The determination of the constants A^* and B appropriate to the problems considered in Section 2f is given in Appendix B.

APPENDIX B

Calculation of c_0, A^* and B

1. Morning glory of the 29th

With $U(z)$ given by Eq. (5), the transformation $\xi = c_0 + U_2 - U_1 z/h$ reduces the linear eigenvalue problem [Eqs. (2)] to

$$[\xi^2\phi_\xi]_\xi + q^2\phi = 0, \tag{B1}$$

where $q = Nh/U_1$, subject to the boundary conditions

$$\phi = 0 \quad \text{at} \quad \xi = c_0 + U_2 = \xi_0, \tag{B2}$$

$$\phi_\xi = 0 \quad \text{at} \quad \xi = c_0 + U_2 - U_1 = \xi_1, \tag{B3}$$

and the normalization condition

$$\phi = 1 \quad \text{at} \quad \xi = \xi_1. \tag{B4}$$

With a further substitution $\xi = \exp(\eta)$, it is easy to show that the solution of Eq. (B1) satisfying Eqs. (B2) and (B4) is

$$\phi = \left(\frac{\xi_1}{\xi}\right)^{1/2} \frac{\sin[\nu \ln(\xi/\xi_0)]}{\sin[\nu \ln(\xi_1/\xi_0)]}, \tag{B5}$$

where $\nu = (q^2 - \frac{1}{4})^{1/2}$, and then the expression for $\phi(z)$ follows immediately. Note that for the 29th, the value of q, essentially a Richardson number for the inversion layer, is ~ 1.5 so that ν is real. Values of $q < 0.25$, implying imaginary values for ν, would lead to unstable Kelvin-Helmholtz modes.

Substitution of Eq. (B5) into Eq. (B3) gives the eigenvalues c_0, i.e.,

$$\left.\begin{aligned} & c_0 = U_2 + \frac{U_1}{e^{\alpha_n} - 1} \\ & \text{where} \\ & \alpha_n = \nu^{-1}\tan^{-1}2\nu + n\pi\nu^{-1}, \quad n = 0, \pm1, \pm2, \ldots \end{aligned}\right\}.$$

It turns out that the gravest mode propagating in the positive x direction corresponds with $n = -1$.

The constants B and A^* given by Eqs. (A3) and (A4), and hence μ, for the model appropriate to the 29th are evaluated numerically with the above data as input.

2. Morning glory of the 4th

For this day we may begin by taking $U \equiv 0$ and applying Example 2 given by Benjamin (1967, 584–586). Then, in our notation, Benjamin's Eqs. (5.18), (5.21) and (5.22) give, for the gravest mode, $c_0 = 2Nh/\pi$, $A^* = \pi^2/8h$, $B = \pi^2/4h^2$ and hence $\mu = 1$. The appropriate translation speed when $U = -2.2$ m s^{-1} is then obtained by subtracting the value 2.2 from the translation speed calculated from Eq. (A8).

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