The bore-like character of three morning glories observed during the Central Australian Fronts Experiment

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Results of a field experiment carried out in 1991 as part of the Central Australian Fronts Experiment (CAFE) are presented. The data include daily early morning radiosonde soundings from Burketown in north Queensland, together with pressure, wind, temperature, and humidity data from an automatic weather station there. Sixteen morning glories were recorded at Burketown during the experiment. Surface data showed that the passage of a morning glory is accompanied by wind squalls, intense low-altitude wind shear and a sharp pressure jump at the surface. On all except one day, radiosonde soundings were carried out in the pre-morning glory environment. On seven days, additional soundings were carried out within an hour or two of the passage of a morning glory. Comparison of these with the pre-morning glory soundings is consistent with earlier inferences that disturbances are a type of internal undular bore. Unlike the one southerly morning glory for which data were obtained, the data for the northeasterly glories indicate significant horizontal temperature and moisture gradients in the post-morning glory air mass in most cases. Nevertheless, the observations are consistent with an internal undular bore generated in a horizontally inhomogeneous air mass.

Introduction

The morning glory is a spectacular travelling wavecloud system commonly observed during the late dry season over the southern part of Gulf of Carpentaria and adjacent seaboard.§ Sudden wind squalls, intense low-altitude wind shear and a sharp pressure jump at the surface generally accompany their passage. The pressure jump is due to pronounced vertical displacements of air parcels which are sometimes sufficient to initiate show-

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§ Places mentioned in the paper are marked on the map shown in Fig. 1.
ers or thunderstorms in the wake of the disturbance when the air over the Gulf is moist enough. Based on early field experiments, Clarke et al. (1981) suggested that the morning glory is a hydraulic jump or bore. Most morning glories propagate across the Gulf from the northeast. They are generated in the late evening on the western side of Cape York Peninsula from the collision of the east and west coast sea-breezes (see Smith (1988) and Christie (1992) for recent reviews). Morning glories which propagate from the south are observed also over the southern Gulf region. It would appear that most of these disturbances are associated with fronts and troughs crossing central Australia (Smith et al. 1986; Smith et al. 1995; Reeder et al. 1995). Recently, Christie (1992) has reported that morning glories are occasionally observed moving from the southeast. The generation mechanism for such disturbances is at present unclear, although night-time convection is a likely candidate.

The present study is based on data taken in 1991 as part of the Central Australian Fronts Experiment (CAFE). The principal aims of CAFE were to investigate the structure and dynamics of subtropical cold fronts that affect central Australia, and to determine the role such fronts play in the generation of southerly morning glories (Smith et al. 1995). A subsidiary experiment was carried out also to obtain upper-air data on the morning glory environment, and to investigate the propagation characteristics of the morning glory waveguide (Menhofer et al. 1997). During the subsidiary experiment, a total of 25 morning glories were observed over a 30-day period from 7 September to 6 October 1991. Of these, 23 formed over the Peninsula and two originated to the south of the Gulf. Only 14 of those that formed over the Peninsula were recorded at Burketown, although both southerly disturbances were recorded there. The disturbances were identified on the Peninsula
by their accompanying surface pressure jumps recorded at Stirling Station. In the present paper, interest is focused on three particular, representative disturbances.

The subsidiary experiment to CAFE was the first in which surface measurements of wind, pressure, temperature, and humidity were taken simultaneously. It was also the first time that radiosonde soundings had been made throughout the troposphere and lower stratosphere, both before and after the passage of disturbances. From 9 September onwards, daily radiosonde soundings were carried out at Burketown in northern Queensland using a Väisälä Marwinsonde system. Most of the radiosondes were released around 0430 EST* in order to document the vertical structure of the pre-morning glory environment. On some occasions a second radiosonde was released within an hour or two of a morning glory passage in order to document the post-morning glory environment; three such occasions form the focus of the present study. These data are used to investigate the structure of three particular morning glories, and to assess the extent to which they can be regarded as undular bores.

**Southerly morning glory on 17 September 1991**

The southerly morning glory on 17 September was marked at Burketown by two well-developed roll clouds. These two were followed by a third dissolving roll cloud. Figure 2 shows digitally recorded two-minute average measurements of pressure, wind, temperature and humidity at a height of 3 m above the ground. The data were taken at Burketown aerodrome during the six-hour period commencing 0500 EST. The disturbance, which arrived at Burketown at 0638 EST, is marked by a sudden rise in the surface pressure followed by a series of oscillations about an increased mean (Fig. 2(e)). Although the first wave has the largest amplitude (1.4 hPa), at least three more waves can be clearly identified. Note also that the strong wind gusts show an oscillatory pattern similar to the pressure (Fig. 2(c)). With the arrival of the leading edge of the disturbance, the surface wind turned from northwest to south-southwest, the direction from which the morning glory approached Burketown (Fig. 2(d)). The leading edge of the disturbance was marked also by small, but sharp rises in the temperature and mixing ratio (Figs 2(a) and (b)).

The passage of a pure bore wave brings about a permanent vertical displacement of the bore-relative streamlines. Therefore, one might expect a permanent (or at least prolonged) rise in the surface pressure following the passage of a morning glory disturbance. Although a continuous rise is indicated in Fig. 2(e), the time series includes the rise due to the diurnal change. The diurnal variation of surface pressure between 0400 and 1600 EST based on the average over 16 days without morning glories at Burketown is shown in Fig. 3(a). Note that the mean surface pressure in this figure reflects not only the diurnal change, but also differences in the synoptic pressure pattern on the days used for the calculation. Shown also in Fig. 3(b) is the result of subtracting the mean diurnal variation from the surface pressure recorded on 17 September. It can be seen that the resulting corrected pressure remained high for more than nine hours after the initial jump. It is notable that the difference between the pressure in the afternoon and the pressure immediately before the jump is 1.4 hPa,

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* Australian Eastern Standard Time = UTC + 10 hours
Fig. 3  (a) The mean daily surface pressure based on 16 days without morning glories reaching Burketown. (b) The pressure on 17 September from 0400 to 1600 after the mean diurnal pressure variation has been removed.

Fig 3: Graphs showing pressure variations at Burketown.

exactly the amplitude of the initial jump. This fact points to the bore-like character of the disturbance. If the disturbance were a series of pure solitary waves, the corrected pressure would return to its undisturbed value after their passage. However, these data do not distinguish between a gravity current and a bore.

Clarke et al. (1981) showed that there were at most only small regions behind the two morning glory disturbances they investigated where the flow in the direction of the disturbance was faster than the disturbance itself. On the basis of this observation they concluded that the disturbance had the character of a bore, rather than that of a (quasi) steady gravity current. Both types of disturbance are associated with cooling. In the case of a bore, the cooling is due to the adiabatic lifting of air parcels, whereas in the case of a gravity current it is primarily a consequence of cold-air advection. In principle, it should be possible to distinguish between a bore and a gravity current by examining the change in surface temperature; there should be no temperature change at the surface without horizontal cold-air advection because the vertical velocity at the surface is zero. In practice, however, the surface temperature change is disguised by vertical mixing. The temperature profiles at 0430 EST on all days of the experiment were characterised by a shallow radiation inversion close to the surface. Turbulent mixing that accompanies the passage of a disturbance, be it a bore or a gravity current, as well as the convective mixing caused by radiative heating after sunrise destroys the inversion, mixing down potentially warmer air. Thus, in either case, the surface temperature rises. Even the advection of cold air, therefore, need not decrease the temperature at the surface, particularly if the cold air arrives within an hour or two after sunrise (e.g., see Event 1, Fig. 6 in Smith et al. (1995)).

Nevertheless, it is still possible to distinguish between the bore-like or gravity current-like nature of a disturbance provided that the mixing is confined to a sufficiently shallow layer. As explained by Smith et al. (1995), this is done by plotting the pre and post-morning glory soundings on a thermodynamic diagram in which the two conserved variables, potential temperature and water-vapour mixing ratio*, are the two coordinate axes. We refer to these thermodynamic plots as θ(w)-diagrams. For a pure bore-like disturbance, the two soundings must coincide, although points on each sounding are at different heights. In other words, the sounding is altered only by adiabatic lifting of the air parcels. By plotting the heights of the air parcels, one can determine the height that a relative streamline is lifted as it traverses the bore. If the temperature decrease is brought about by horizontal advection, as in a gravity current or any other air-mass change, the two soundings will be quite different. Smith et al. (1995) analysed the morning glory of 17 September this way and showed that it had a pronounced bore-like signature. In the following sections we analyse two of the northeasterly morning glories for which a second sounding was obtained in the same manner.

Northeasterly morning glory on 25 September 1991

The northeasterly morning glory on this day arrived at Burketown at 0450 EST and was not accompanied by cloud. Figure 4 shows time series of the surface temperature, mixing ratio, wind direction, wind speed and corrected pressure. Like the southerly morning glory on 17 September (Fig. 3(b)), the surface pressure trace suggests that the disturbance was dynamically similar to an undular bore. A sharp pressure jump marks the leading edge of the disturbance, followed by a series of undulations and permanent rise in the pressure. Note that the temperature rose sharply also at the leading edge of the disturbance because of the downward turbulent mixing of potentially warmer air.

The pre and post-morning glory profiles of virtual potential temperature and mixing ratio, taken at 0429 EST and 0630 EST respectively, are plotted in Fig. 5. Although weaker, the surface inversion was still intact in the post-morning glory sounding (Fig. 5(a)), and had actually deepened following the disturbance, with the nearly neutral layer starting at a height of around 1.4 km

* Strictly, it is the total water (vapour + condensed) that is conserved, but the morning glory clouds re-evaporate and both pre and post-disturbance radiosonde soundings were made in clear air. Of course, the assumption of conservation neglects possible turbulent mixing associated with the disturbance.
Fig. 4  Automatic weather station records at Burketown aerodrome on 25 September 1991 from 0200 to 0800 EST. (a) Temperature, (b) mixing ratio, (c) wind direction and (d) corrected pressure from 0400 to 1600 EST. The morning glory passed at 0450 EST.

Fig. 5  (a) Vertical profiles of virtual potential temperature below 5 km on 25 September 1991. The solid line represents the pre-morning glory profile, and the dashed line the post-morning glory profile. The passage of the northeasterly morning glory occurred at 0450 EST. (b) As in (a), but mixing ratio. (c) Virtual potential temperature as a function of mixing ratio. The numbers indicate the height, z(θ), of air parcels at 500 m intervals for each profile.
Subsequent nocturnal radiative cooling produces dew and sometimes even a shallow layer of fog. After sunrise, the fog layer disperses and surface evaporation moistens the near-surface air. Convective mixing then redistributes the moist air vertically. As explained above, on 25 September a second strong increase in the surface mixing ratio was observed before 0700 EST, starting around the time that the second radiosonde was released. This increase in moisture occurred one and a half hours after the change in surface wind direction, and it can be assumed that at this stage, the advection of relatively moist air had already commenced. The more humid air may have been associated with horizontal gradients in the air mass. The model results of Noonan and Smith (1997) support this assumption. Figure 3 in their paper shows a strong westward gradient in potential temperature below 2000 m over the southern part of the Peninsula and the Gulf. The jump of the isentropes occurs near the western side of the peninsula by 2200 EST and translates westward until the following morning. This pattern was repeated on each day of their simulation.

In summary, the soundings plotted in Fig. 5 show that the low-level pre-morning glory air was lifted by about 1000 m (compare air parcels at 500 m and 1500 m, or 1000 m and 2000 m in the pre and post-disturbance soundings, respectively, in Fig. 5(c)). It appears that by 0630 EST, a moister air mass originating from the gulf had replaced the original air below 800 m, suggesting significant horizontal temperature and moisture gradients in the post-morning glory air mass. Nevertheless, the observations are consistent with an internal undular bore generated at the leading edge of a horizontally inhomogeneous air mass, where the inhomogeneity is provided by the land-sea boundary to the north of Burketown.

**Northeasterly morning glory on 2 October 1991**

At 0656 EST on 2 October 1991, three low roll clouds with thin strips of cloud a few thousand meters higher were observed. The higher clouds were estimated to lie at a height of about 4 km. At 0745 EST another moderately high cloud strip approached Burketown from the east, followed by a low roll cloud at 0805 EST. The disturbance was characterised by a series of oscillations in the surface pressure, extending over more than one hour.

Three radiosonde soundings were carried out on this occasion: the first as usual at 0430 EST, the second at 0812 EST while the morning glory was passing over Burketown, and the third after its passage at 0900 EST. The virtual potential temperature and mixing ratio profiles from the three soundings are plotted in Figs 7(a) and (b). In the lowest 1 km, the second profile is cooler than the first by about 5 K, except in the lowest 250 m
Fig. 7  (a) Vertical profiles of virtual potential temperature on 2 October 1991. The solid line represents the first sounding at 0430 EST, the dashed line the second at 0812 EST, and the dotted line the third at 0900 EST. A north-easterly morning glory passed at 0656 EST, topped by mid-level cloud strips, and another low roll cloud followed at 0805 EST. (b) As in (a) but mixing ratio. (c) Virtual potential temperature as a function of mixing ratio at 0430 (solid line) and 0812 EST (dashed line). The numbers indicate the height, z(θ), of the air parcels at 500 m intervals. (d) As in (c), but for the soundings at 0812 (solid line) and 0900 EST (dashed line). (e) As in (a), but equivalent potential temperature.

where the passage of the disturbance together with insula-

tion have destroyed the nocturnal inversion. Between

the heights of 300 m and 1700 m, the second profile is

also moister than the first. Likewise the third profile is
cooler and moister than the second.

The θ(w)-diagram for the first two profiles (Fig. 7(c))

shows that air at all heights between 300 m and 2000 m

was lifted by about 500 m. Since the atmosphere was

neutrally stratified above 1500 m (Fig. 7(a)), lifting

would not cause cooling in this layer. Similarly, the mix-
ing-ratio profile, which is roughly constant between

1500 m and 2000 m, was affected little by lifting within

this layer. The difference between the θ(w)-profiles at

low levels was due to insolation which increased the tem-

perature in a shallow layer above the ground (Fig. 7(a)).

The θ(w)-diagram for the second and third profiles is

plotted in Fig. 7(d). There is now a major difference

between the profiles. The third profile is much cooler

drier than the second between about 1000 m and

about 2500 m. Presumably, this change was caused by

horizontal advection, as it could not have been due to

adiabatic lifting. Figure 7(e) shows the profiles of equiv-

alent potential temperature for the three soundings. Note

that the third sounding shows a decrease in equivalent

potential temperature of more than 5 K above 1500 m,

consistent with the θ(w)-diagram. Below 1400 m the
winds were northerly in all three soundings, whereas from 1400 m to 2500 m the wind turned from an easterly in the first sounding to a southerly in the second. In the third sounding, the winds were northeasterly below 2200 m, turning southerly above that. This suggests that relatively dry continental air originating from regions farther south had replaced the original air mass above 1400 m by 0900 EST.

In summary, alteration in the structure of the atmosphere after the passage of the leading edge of this morning glory is consistent with that of an undular bore. On the assumption that the atmosphere was affected by the bore up to almost 3 km, the observed mid-level strips of cloud which lay above the single low roll clouds are likely to have been due to the bore. The observations of glider pilots soaring on the disturbance suggest that the upper-level clouds were produced by vertical displacements of the upper-level inversion at a height of about 4.3 km. Internal gravity waves can be excited in the free atmosphere above the nearly neutral layer. The character of the disturbance which caused the changes at upper levels between 0812 and 0900 EST remains uncertain. It is unusual that continental air from the south is not only drier, but also cooler than the air from northeast. The reason for this may be connected to a cold front over central Australia which passed Alice Springs on 2 October at 0200 EST. Figure 26 in Smith et al. (1995) shows a decrease in potential temperature extending to a height of 3 km after the front passed Alice Springs. On the other hand, Smith et al. (1995) did not find evidence of a surface front farther north than Tobermory Station and Aradagadaga, both of which lie well to the south of Burketown (Fig. 1). They concluded that the front dissolved far to the southwest of the Gulf region. Notwithstanding this, there may have been cold-air advection over the continent at some level above the surface.

Summary and conclusions

In 1991 sixteen morning glories were documented during the subsidiary experiment to CAFE. Modifications to the atmosphere associated with the passage of morning-glory disturbances were studied using time series of surface data and radiosonde soundings in the pre and post-morning glory environments. In each case, the passage of a morning glory was characterised at the surface by wind and pressure oscillations, and by a small rise in temperature caused by the destruction of the nocturnal radiation inversion. A change in the surface wind direction from westerly to northeasterly accompanied the passage of northeasterly morning glories, while a change from westerly to southerly accompanied the southerly morning glory on 17 September. Surface pressure jumps with amplitudes between 0.5 hPa and 1.5 hPa were recorded at the leading edge of the morning glories. The initial jumps were followed by one or more undulations with decreasing amplitude. Subtraction of the mean semi-diurnal change in pressure showed that the surface pressure remained high for several hours after the passage of all morning glories except the one on 10 September 1991. This is as one might expect, since the passage of a bore permanently displaces the streamlines in the vertical. The exception on 10 September was a morning glory which reached Burketown in the late morning in its decaying stage, and only a weak pressure jump was recorded before the pressure returned to its pre-disturbance value.

The structure of three representative morning glories has been investigated in detail. Above the surface-based inversion, the passage of each disturbance cooled the atmosphere through a layer ranging in depth from 500 m to 2 km. The dynamical character of the disturbances was investigated by plotting the potential temperature from the radiosonde soundings as a function of the mixing ratio. On the basis of this analysis, the southerly morning glory was shown to have the character of a bore. In the two northeasterly disturbances, temperature and moisture advection appeared to have played a part in modifying the post-morning glory sounding. At times there can be significant horizontal gradients in the gulf region, and by implication, significant horizontal inhomogeneities in the wave-guide. A study of the relative winds revealed that there was no change in sign between the pre and post-morning-glory soundings. Therefore, no low-level feeder flow existed, confirming that morning glories are not gravity currents.

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References


