Morning glory wind surges and the Gulf of Carpentaria cloud line of 25-26 October 1984

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Observational data on three ‘morning glory’ wind surges, which occurred in the southern part of the Gulf of Carpentaria region of northern Australia on two consecutive mornings (25 and 26 October 1984), are presented together with a summary of surface synoptic analyses and satellite imagery for the period. On 25 October a wind surge from the south, which passed over Burketown at about 0515 local time, was followed about four hours later by one from the northeast. On 26 October a large amplitude and unusually coherent wave disturbance was associated with a southerly surge in the early morning hours (about 0130 at Burketown). Aircraft temperature soundings ahead of and behind the two surges of 25 October showed significant cooling following the passage of the surge, indicative of its origin as a gravity current, and consistent with a few other documented cases. The northeasterly surge of 25 October was investigated from the air in a region over the Gulf some 100 km northeast of Burketown. There a line of convective cloud appeared to mark its leading edge, while the evidence is that further to the southeast the leading edge was marked by a series of typical morning glory wave clouds. The latter were imperceptible and the former barely discernable in the Geostationary Meteorological Satellite infrared imagery. They were both striking in high resolution visible imagery from the NOAA 6 polar orbiting satellite, but even then the two types could not be distinguished. The synoptic data are suggestive of a possible link between the northward movement of an inland trough during the night and the genesis of the southerly surges. The low-level wind data highlight the role of nocturnal wind surges which, together with sea and land breeze circulations, contribute significantly to the diurnal variability of wind structure below 2 km in the southern Gulf region.

Introduction

The southern part of the Gulf of Carpentaria region of northern Australia has become well known for the relatively frequent occurrence there of strong nocturnal wind surges, often accompanied by spectacular propagating wave-cloud lines — the so-called ‘morning glory’ phenomenon (Clarke et al. 1981; Smith et al. 1982; Christie and Muirhead 1983; Clarke 1983; Smith and Morton 1984, henceforth referred to as SM; Smith et al. 1986, henceforth referred to as SCE). In addition, the entire Gulf region is known by local meteorologists as one where there commonly occurs extensive lines of convective cloud, sometimes 500 km or more in length, and orientated typically from the north-northwest to south-southeast. Such clouds have been referred to recently as North Australian Cloud Lines (NACLs) and appear to be important components of the meteorology of the region (Holland, personal communication). The relationship of northeasterly morning glory-type wind surges and the NACL has yet to be determined, but some recent numerical simulations of Noonan and Smith (1986) and observations reported herein provide some insight on this question.

The occurrence of southerly morning glories was apparently unsuspected by the meteorological community until quite recently, although these phenomena would have been known to local residents of the southern Gulf region. It appears now that such disturbances are common, but their origins are much less certain than for disturbances from the northeast and they have been less well documented (a review of current knowledge is contained in SCE).

During a field experiment in Burketown in October 1984, run by Monash University with cooperation from the Bureau of Meteorology, three significant
surges occurred during a twenty-four hour period. One from the south just before daybreak on 25 October was followed some four hours later by one from the northeast. In the early hours of the following morning a large amplitude and unusually coherent wave disturbance accompanied the passage of a second southerly surge. Hereafter we designate these surges as events S1, NE1 and S2, respectively. Following aircraft soundings of temperature and humidity ahead of and behind S1, an aerial reconnaissance was made of a convective cloud line some 120 km east-northeast of Burketown over the Gulf. Satellite imagery at about this time and later aerial observations confirmed that this cloud line formed the northern extension of NE1. Regrettably, no observations were made of the interaction between S1 and NE1 which must have occurred east of Burketown between 0715 and 0800*. Nevertheless, aircraft soundings were made ahead of and behind NE1 between 0815 and 0945, and serial pilot balloon wind determinations were made during the morning.

Event S2 occurred much earlier than is apparently usual and most of our data on it are from a network of six anemographs and two barographs. Eyewitness accounts say that it was accompanied by spectacular roll clouds, but these clouds are not visible in the infrared GMS imagery as is normally the case.

The synoptic situation

It is well documented that morning glory wind surges are relatively shallow phenomena confined predominantly to the lowest few kilometres of the atmosphere (Clarke et al. 1981; SM; SCE). On this account one would expect the large-scale environment conditions conducive to disturbance formation to be characterised by the synoptic conditions at mean sea level (MSL). Figure 1 shows the MSL isobaric charts for 0900 on 24, 25 and 26 October 1984 (henceforth we refer to these days as the 24th, 25th and 26th). Prominent features on the 24th are the anticyclones centred in the Indian Ocean at about longitude 100°E and in the Tasman Sea at about longitude 165°E. The former had a ridge extending across the south of Western Australia, while the latter formed a ridge along the east coast of Queensland. Pressure gradients over the Gulf and to the south of it were slack, a situation favourable to the deep inland penetration of the sea-breeze from the southern Gulf coast (Physick and Smith 1985). During the next twenty-four hours the ridge over Western Australia strengthened to form a 'bubble' high pressure centre over the Great Australian Bight and associated pressure rises occurred over much of central Australia. In contrast, the ridge along the east coast of Queensland remained, but weakened slightly as measured by the pressure difference between Cairns and Thursday Island (see Table 1). On the 26th the high and the ridge had merged leaving a sharp trough extending south-southeastwards from the Gulf across inland Queensland, the high centre having moved southwards to southeastern Australia. The ridge along the east coast of Queensland had slackened considerably by this time. Not so clearly

* All times are Eastern Standard Time = Greenwich Mean Time + 10 hours.
Table 1. Mean sea level pressure difference $\Delta p$ (mb) between Cairns and Thursday Island at 0900 on days of interest.

<table>
<thead>
<tr>
<th>Date</th>
<th>$\Delta p$</th>
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<tr>
<td>24/10/84</td>
<td>3.6</td>
</tr>
<tr>
<td>25/10/84</td>
<td>3.0</td>
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<tr>
<td>26/10/84</td>
<td>1.7</td>
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apparent from these diagrams is the northeastward advance of a sharp trough during the early hours of both the 25th and 26th as evidenced by the north Queensland regional analyses. Successive positions of the trough axis at 0300, 0600 and 0900 on these days are shown in Fig. 2†. On the morning of the 25th the trough axis advanced steadily at about 10 ms$^{-1}$, but was some 600 km southwest of the leading edge of S1 when the latter passed over Burketown. The advance was discontinued during the day due presumably to the strengthening of the inland heat trough (cf. Smith et al. 1982, p.953; SCE) but resumed on the 26th. Again the trough axis lay over 200 km south of S2 when the leading edge of this disturbance passed over Burketown. The position of the trough axis at 0900 on 26 October is about the most northerly position reached, again a contributing factor being the daytime strengthening of the inland trough.

At the time of writing, the dynamical relationship, if any, between the movement of the trough and the southerly wind surge ahead of it has not been determined, but the former appears to be the most prominent synoptics precursor to the surge.

**Satellite imagery and aerial photography compared**

In general, wave-cloud lines associated with the leading edge of morning glory- type surges are difficult to identify in satellite imagery. The resolution and contrast afforded by the GMS infrared (IR) photographs is insufficient to distinguish these low-level clouds, whose lifetime extends mostly during hours of darkness. Even the visual channel of polar orbiting satellites, which gives better contrast at low levels and much higher resolution, is barely adequate. Thus, neither S1, which was not marked by a significant cloud roll until it crossed from the land out over the Gulf, nor S2, which according to eyewitnesses was accompanied by impressive cloud rolls, could be identified in the GMS-IR imagery. Moreover, while the NE1 cloud line was clearly recognisable in the NOAA-6 visible high-resolution imagery at 0719 (Fig. 3), the cloud type could not be identified. Indeed aerial observations one hour earlier showed that the cloud line was convective over the Gulf with cloud tops extending to 3 km (Fig. 4), but similar observations shortly after the satellite photograph was taken showed that the southern end of the cloud line over the land was distinctly wavelike (Fig. 5). That this difference is not simply attributable to the temporal evolution of the cloud line between aircraft observations is supported by the reported sighting of morning glory roll clouds at Normanton at about 0600 by the Bureau of Meteorology observer there. This is corroborated by the GMS-IR imagery at 0600, in which the convective line over the Gulf is just visible, but the lower wave clouds to the south are not.

Of some interest is the sharp bend in the cloud line evident in both the satellite photograph (Fig. 3) and the aerial photograph (Fig. 5). Aerial measurements showed the bend angle to be approximately 30°.
would appear from Fig. 3 that the bend marks the point along the cloud line, to the south of which the disturbance had a trajectory completely over the land. It is tempting to speculate that it may be caused by the different propagation characteristics due to either a significantly different static stability or different frictional effects on the disturbance over the land compared with those over the sea. Unfortunately, the data to appraise this are unavailable.

While synoptic conditions on the 24th and 25th were favourable for morning glory formation, they appeared favourable also for the formation of the NACL as described by Holland (personal communication). The NACL is a line of convective cloud that forms on the northwestern side of Cape York Peninsula during the early evening (typically around 1900-2000) and propagates westwards at a speed similar to that of the morning glory, typically about 10 m s⁻¹. Under certain synoptic conditions which have not been fully determined, NACL formation is a daily occurrence and cloud lines may retain their identity for one or two days as they

Fig. 4 North Australian Cloud Line of 25 October 1984 taken at about 0630 approximately 100 km east-northeast of Burketown. View is towards the northeast.
migrate westwards. The precise relationship between the NACL and the morning glory has yet to be established, but the observations reported here support the idea that there is a close connection between the two phenomena. Indeed, it would appear that, at least in the southern part of the Gulf region, the wave disturbance which constitutes the leading edge of the morning glory surge initiates the NACL when the air is sufficiently conditionally-unstable. Some recent numerical model simulations (Noonan and Smith 1986) suggest that further north the NACL is triggered directly by the interaction of the east and west coast sea-breezes in much the same way as the morning glory itself (Clarke 1984). The narrower width of the Peninsula in the north appears to have two important consequences. Firstly, interaction of the two sea-breezes occurs earlier than further south; in fact, with an easterly geostrophic wind speed of 5 m s\(^{-1}\), the model predictions give a time of around 1900-2000, the time at which the NACL normally forms. Indeed, on both the 24th and 25th, the collapse of the west coast sea-breeze at Weipa, in favour of a steady easterly, occurred between these times. Secondly, the model predicted depth and westwards extent of the convectively well-mixed layer advected over the Gulf from the Peninsula is also less than it is further south. This would provide for a less effective wave guide for the propagation of a morning glory-type disturbance. Nevertheless, the model suggests that synoptic conditions required for the NACL formation would be similar to those required for morning glory genesis; namely a moderate easterly geostrophic wind component across the Peninsula.

Low-level winds

Figure 6 shows the vertical profiles of horizontal wind components \((u,v)\) in the eastward and northward directions \((x,y)\) at Burketown at selected times during the period of interest, while Fig. 7 shows time-height cross-sections of these components on the morning of the 25th. The major changes during the period occur mostly below 1.5 km, above which the winds are generally from the southeast sector — the climatological norm at this time of year. About half an hour after the passage of S1 the winds below 350 m were from the northwest sector (Fig. 6(a)); the westerly component showing a sharp maximum of about 6.0 m s\(^{-1}\) at 150 m, reminiscent of a typical nocturnal jet in this region (cf. SM, Fig. 14; SCE, Fig. 7). Regrettably, no sounding was obtained prior
to the passage of the surge. The winds below about 300 m diminished in intensity a little after sunrise (about 0600), but above this level remained remarkably uniform until about 0845, shortly before the onset of NE1 at 0930 (Fig. 7(a)). Thereafter, the westerly component below 350 m was replaced by an easterly one and the existing easterly component above this level was strengthened for an hour or so. The onset of NE1 brought also a strengthening of the northerly component and this strengthening continued during the day, presumably due to the sea-breeze influence (Fig. 7(b)). By about 2130 that evening the sea-breeze was evident as a strong northwesterly flow below about 600 m, the maximum speed being 13 m s\(^{-1}\) from 340 deg. at 430 m (Fig. 6(b)). By 0545 on 26 October, four hours after the

Fig. 7 Time-height cross-sections of wind component isotachs at Burketown on 25 October 1984: (a) westerly component, u; (b) southerly component, v. The dots represent successive 30 s pilot balloon positions and provide an indication of the resolution involved in the construction of the isotachs. The contour interval is 1 m s\(^{-1}\).
passage of S2, the sea-breeze had become replaced by strong southwesterlies with a maximum of 10 m s\(^{-1}\) from 245 deg. at 460 m (Fig. 6(c)). These data highlight the role of morning glory-type surges which, together with the sea and land breeze circulation, contribute significantly to the diurnal variability of low-level winds in the southern Gulf region.

Surface anemograph traces spanning the period of onset of S2 are shown in Fig. 8 for four locations (Lorraine Station, Augustus Downs Station, Floraville Station and Armraynald Station) roughly along a line extending approximately 140 km south-southwest of Burketown. The disturbance onset was marked in each case by a sharp transition from north-northwesterlies (a sea-breeze regime) to southwesterlies between midnight and 0200, followed by a series of oscillations in wind direction with a period of 15 to 20 minutes. At Armraynald, the most northerly of these stations, the oscillations persisted for some two hours. Following the passage of the disturbance the surface winds at all stations became calm for several hours. The surface pressure at Burketown and at Doomadgee (100 km west of Burketown) rose on the order of 1.5 mb with the passage of the disturbance and thereafter oscillated with a period comparable with the wind oscillations as is typical for northeasterly morning glory surges also. The velocity of propagation of this disturbance, estimated from the onset times at seven anemograph locations (the foregoing stations together with Burketown, Doomadgee and Mornington Island) as described in SM (p.157), was 17.4 \(\pm\) 0.4 m s\(^{-1}\) from 204 \(\pm\) 2 deg. The speed is the highest so far documented for morning glories, but is comparable with those found for the more intense southerly surges (SCE, Table 1). Significantly, it is about 70 per cent higher than is usual for northeasterly morning glories. The reason why some southerly surges move with such relatively high speeds has not been determined.

Unfortunately, no estimate of propagation speed was possible for S1 as there was ambiguity in the onset times in all but two of the seven anemograph traces referred to above. These anemographs comprise the western network. A further anemograph was located in Karumba, 140 km east-northeast of Burketown, but neither S1 or S2 were evident in the trace from this.

The estimated mean velocity of NE1 between

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Fig. 8 Woelfle anemograph traces for the early morning of 26 October 1984 at the locations indicated. Time corrections are as indicated.
Karumba and the anemograph stations to the west is $10.0 \pm 0.4$ m s$^{-1}$ from $75.1 \pm 0.2$ deg. However, excluding the onset time at Karumba, the velocity through the western network is a mere $3.6 \pm 0.5$ m s$^{-1}$ from $73 \pm 1$ deg., indicative of a strong retardation. The retardation could probably be attributed to the erosion of the low-level stable layer by convective mixing after sunrise (see Fig. 10 below). The slow speed of translation over the Burketown region was evident also from time lapse movies of the associated cloud line.

**Temperature and humidity soundings**

Figure 9 shows vertical profiles of virtual potential temperature $\Theta_v$, ahead of and behind S1, based on aircraft soundings. The temperature and humidity measurements themselves were obtained from Vaisala humicap sensors mounted on the nose of the aircraft, a twin-engined Beechcraft Travelair. As is usual, the thermal structure shows a shallow stable layer a few hundred metres deep underlying a deep well-mixed layer of uniform $\Theta_v$. Of particular interest, however, is cooling in the lowest 500 m, amounting to several degrees, following the disturbance passage. Two soundings made during ascent from, and descent into, Burketown about 20 minutes and 90 minutes after the disturbance passed over the town showed very close agreement. The mean of these is shown in Fig. 9. The cooling found here is consistent with the only other such measurement made in a southerly surge (SCE, Fig. 9(a)) and seems to be a general feature of surges (cf. SM, Fig. 21, and Fig. 10 below). In particular, it is strongly suggestive of the gravity-current origin of the disturbance. Finally, it may be worth recording that the depth of cooling was somewhat less than the height of the associated cloud line, the top of which was measured by the aircraft to be at 1200 m.

Similar profiles of $\Theta_v$ ahead of and behind NE1 are shown in Fig. 10. Again there is evidence of some cooling following the disturbance passage, but the cooling is through a deeper layer and does not extend to the surface. This may be due to the fact that the sounding behind was made some 40 minutes after

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**Fig. 9** Vertical profiles of virtual potential temperature based on aircraft soundings ahead of and behind the southerly surge of 25 October 1984.

**Fig. 10** Legend as for Fig. 9, but for the northeasterly surge. The broken line corresponds with a sounding at 0645, one and a half hours before the sounding immediately ahead was made.
the sounding ahead, during which time strong convective mixing was in progress. Unlike S1, where there was little change in the vertical structure of moisture before and after passage, there was a considerable increase in moisture following the passage of NE1 (Fig. 11). Accordingly the actual cooling is slightly larger than one would infer from Fig. 11 as evidenced from plots of potential temperature (not shown). The moisture profile before the passage is much the same as in the soundings on which Fig. 9 is based.

The Θ, sounding on the aircraft descent into Burketown at 0645 is included in Fig. 10 to give an idea of the rate at which the stable layer was being eroded by convective mixing in the intervening time before the ascent ahead of NE1 at 0815.

**Conclusions**

The data presented here exemplify important aspects of the dry-season mesostructure of the Gulf of Carpentaria region. They highlight, for example, the significant contribution of undular bore-type surges from both the northeastern and southern sectors to the temporal variability of low-level winds (below 2 km) in the southern Gulf region, and show that under suitable synoptic conditions surges from both sectors can occur on the same day. The aircraft observations coupled with those from satellites on 25 October point to a connection between the North Australian Cloud Line and the morning glory phenomenon, at least in the southern Gulf region. The aircraft observations show also the inadequacy of satellite imagery alone in the identification of morning glory wave-clouds. The data on the two southerly surges add significantly to the total data set on this type of disturbance, while of similar importance are the data relating to the cooling following the passage of S1 and NE1. Finally, the synoptic analyses point to a possible relationship between the nocturnal movement of an inland trough and the genesis of southerly surges, but the dynamical basis for such a relationship remains to be explored.

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