# Southerly Nocturnal Wind Surges and Bores in Northeastern Australia

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ABSTRACT

Observational data are presented on southerly nocturnal wind surges, which sometimes give rise to spectacular "morning glory"-type roll clouds in the southern part of the Gulf of Carpentaria region of northern Australia. Like their more frequent northeasterly counterparts in the region, southerly surges are shown to have the character of an undular bore propagating on the nocturnal low-level stable layer. Synoptic mean sea level pressure patterns conducive to the formation of southerly surges are identified and possible mechanisms for the genesis of surges are discussed. The possibility that some southerly surges are generated by the movement of a front across central Australia, as suggested by Smith et al., does not appear to be the most usual generation mechanism. In fact, an analysis of time–height cross sections of velocity components derived from six hourly rawinsoundings from Mount Isa point to a strong association between the occurrence of southerly surges and the formation of the nocturnal jet over the continent. We are led to the hypothesis that many southerly surges are spawned in the interaction between the inland nocturnal jet and the sea breeze front which originates from the southern coast of the gulf. Others may be the result of katabatic drainage from the Barkly Tablelands, but at present the data are inadequate to assess the importance of this mechanism. The paper concludes with a discussion of the extra difficulties in synoptic analysis and forecasting in the region south of the gulf presented by the occurrence of these southerly surges.

## 1. Introduction

In the last few years a number of observational expeditions have been organized to the Gulf of Carpentaria region of northern Australia to study the "morning glory" phenomenon. Morning glory is the name given to an often spectacular low roll cloud or succession of roll clouds, sometimes stretching from horizon to horizon, which occur early in the morning, most frequently towards the end of the late dry season from early September to about mid-November. The clouds are typically 1 or 2 km in width, 1 km deep, and may be 100 km or more long, with cloud bases often no more than 100 or 200 m high. They move rapidly across the sky at speeds of 10–15 m $s^{-1}$, the most usual direction being toward the southwest, although cloud lines orientated approximately east–west and moving from the south are sometimes observed. The passage of each cloud overhead is usually accompanied by the onset of a sudden wind squall which, although normally of short duration (perhaps 5 to 10 minutes), brings wind speeds comparable to the speed of the cloud. The onset of the disturbance brings about an abrupt reversal in surface wind direction which frequently persists for at least several hours. Some of the earliest studies of the phenomenon are as recent as those of Clarke (1972) and Neal et al. (1977); later references are cited below.

Following the first major expedition in 1979, described by Smith and Goodfield (1981), the morning glory phenomenon was identified structurally as an undular bore on a stable layer of air in the lowest half-to-one kilometer of the atmosphere (Clarke et al., 1981). The clouds were found to be essentially wave-type clouds associated with the constituent bore waves. When the bore moves into drier air, as often happens as it moves inland after crossing the southern part of the Gulf, the clouds may dissipate while the bore remains. Thus, Clarke et al. (1981) emphasize the squall-like nature of the disturbance rather than the cloud accompanying it, since disturbances unmarked by cloud are common over land. Recently, the term "wind surge" has been adopted (Clarke, 1983a,b; Smith and Morton, 1984) to describe the overall disturbance. It may be noted that because of strong convective overturning, the low-level stable layer over the land rarely survives into midmorning; however, there is evidence from surface microbarograph data that disturbances continue to propagate in some form for a considerable distance inland during the day (Christie et al., 1978; Christie, personal communication, 1985). The nature of the wave guide at this stage has not been determined.

Northeasterly morning glories have been shown to originate during the late evening over the western side of Cape York Peninsula when, assisted by the prevailing wind, the east coast sea breeze crosses the peninsula and encounters the sea breeze from the west coast of the peninsula (Clarke et al., 1981; Clarke, 1983b). The origin of morning glories from the south, or southerly nocturnal wind surges, is still uncertain, but it is known that these have the essential bore-like structure of their northeasterly counterparts (Smith et al., 1982). What is especially remarkable is that with a few exceptions they tend to occur at Burketown (see Fig. 1 for locations) at much the same time as northeasterly ones, between about 0500 and 0800 EST. (Henceforth, unless otherwise stated, all times are eastern standard time = GMT + 10 hours.)

This paper presents an analysis of data on southerly surges gathered principally during expeditions in the years 1979 to 1982 inclusive, 1984, and from an anemograph network deployed during September 1983. It is organized as follows: Section 2 outlines the data available and briefly summarizes two previous reports of southerly morning glories, while section 3 updates the knowledge derived from an earlier study of the structure of southerly surges. Section 4 seeks to identify synoptic pressure patterns conducive to the formation of southerly surges, and section 5 goes on to explore the possible origin of surges. The implications for synoptic analysis and forecasting are considered in section 6.

## 2. Documented occurrences of southerly surges

We first became aware of the occurrence of southerly surges in the gulf region on witnessing a spectacular morning glory of this type at Burketown about 0700 on 6 October 1979. Prior to the disturbance onset, unusually dense fog lay over the Burketown region, but with the first strong wind squall of the surge, the fog cleared abruptly and an east–west oriented wall of fog, presumably marking the leading edge of the surge, moved away to the north. (See Smith et al., 1982, Fig. 2.) A few kilometers behind this wall and parallel with it, there was a well-formed roll cloud. Unfortunately, this disturbance occurred on the day following the last day of operations of the 1979 expedition when all instruments had been packed away for the return journey south. Therefore, few data on this event are available, other than those obtained routinely by the Bureau of Meteorology. An exception is two excellent satellite photographs taken three hours apart by the DMSP (Defense Meteorological Satellite Program) satellite. A brief discussion of this event is given by Christie et al. (1981), and one of the satellite photographs is presented in their Fig. 4.

During a small and brief but highly successful expedition the following year, six morning glories occurred in Burketown on six consecutive mornings, two of them (on 9 October and 12 October) from the south (Smith et al., 1982). The data on these events included pibal ascents before and after the disturbance passage and detailed surface pressure measurements and showed for the first time the bore-like nature of southerly surges in the Gulf region. The surge of 12 October was accompanied by a large and impressive long smooth roll cloud (see Smith et al., 1982, Fig. 10, and the cover photograph of *Weather,* May 1981), which was reported by residents to have been seen earlier that morning at Gregory Downs, over a hundred kilometers southwest of Burketown. A few weeks later our attention was drawn to a narrow cloud line, extending approximately from west-northwest to east-southeast across the southern part of the gulf and across Mornington Island, in the high resolution satellite photograph for 0900 on 6 November 1980 (Fig. 2). A second cloud line, about thirty kilometers to the north and parallel with the first line, is visible to the east of Mornington Island and over the western part of Cape York Peninsula. These cloud lines may identify a southerly surge, and as we shall see later, synoptic conditions are favorable for the occurrence of a surge, but available surface data are not adequate to positively confirm this. In particular, weekly barograph traces at Normanton and Mornington Island do not show obvious signatures at appropriate times.

In the later expeditions in 1981 and 1982, several more southerly surges were documented in varying degrees of detail, and a number also were recorded in September 1983 as they passed over an anemograph network which had been deployed in the region south of the gulf. In 1981, southerly surges with cloud were observed on three consecutive days; in one of these, on 21 October, 12 pibal soundings were made and an aircraft sounding of temperature structure was obtained ahead of it. A photograph of the leading cloud is shown in Fig. 3. On the following morning, at Macaroni Station on Cape York Peninsula, the southerly surge was preceded by one from the northeast, but the latter did not reach Burketown. During the 1982 expedition, a significant southerly surge occurred on 15 October at Burketown, but was without cloud there. For this event, a radiosonde sounding was made prior to its passage, and pre- and postdisturbance pibal soundings were obtained also, along with a good surface pressure record. On 20 October, two large amplitude wave disturbances from the southwest were recorded at Burketown about two hours after the passage of a northeasterly surge. A few weeks before the 1982 expedition, on 18 September, the passage of a large morning glory from the northeast coincided over Burketown with a somewhat weaker one from the south. A unique photograph of

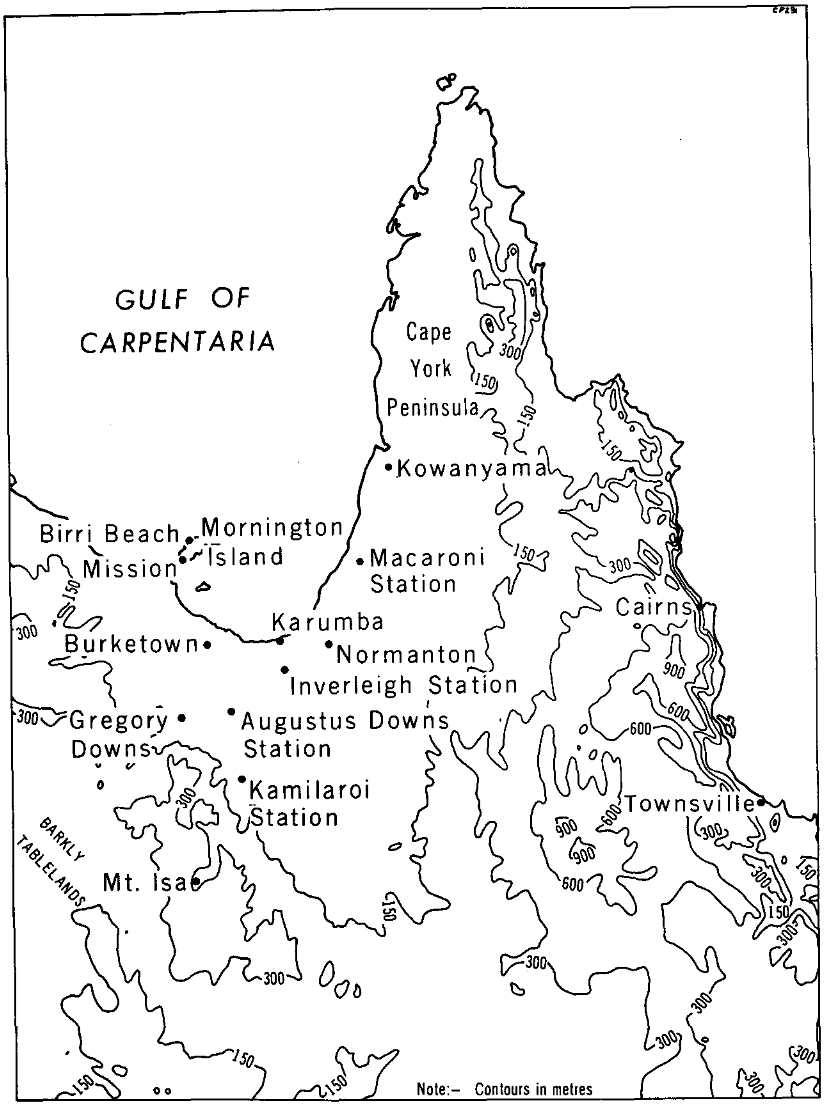


FIG. 1. A location map of places mentioned in the text.

the interaction of these disturbances is shown in Fig. 4.[1] Two clear examples of southerly surges on 9 September and 15 September 1983 were evident in analyses of wind records from the anemograph network, but little other data are available for these cases. Finally, two southerly surges occurred during the 1984 expedition: one on 25 October at Burketown was followed some hours later by a more intense northeasterly surge and a large amplitude disturbance was recorded through our surface instrument network in the early hours of the following morning. Temperature and humidity soundings using the instrumented light aircraft were obtained ahead of and behind the former disturbance.

[1] Photograph by Bernie O'Brien, Burketown.

These various events, details of which are summarized in Table 1, provide the basis for the present analyses.

## 3. Structure of southerly surges

Time series of surface pressure for five southerly surges are shown in Fig. 5; these are based on manual readings from a sensitive digital aneroid barometer taken mostly every minute, or in some cases every half minute. As with northeasterly surges (see, e.g., Clarke et al., 1981; Christie and Muirhead, 1983; Smith and Morton, 1984), these southerly surges display a range of behavior from the large amplitude and distinctly undular traces of the ninth and twenty-second to the large and apparently less wave-like trace of the twelfth

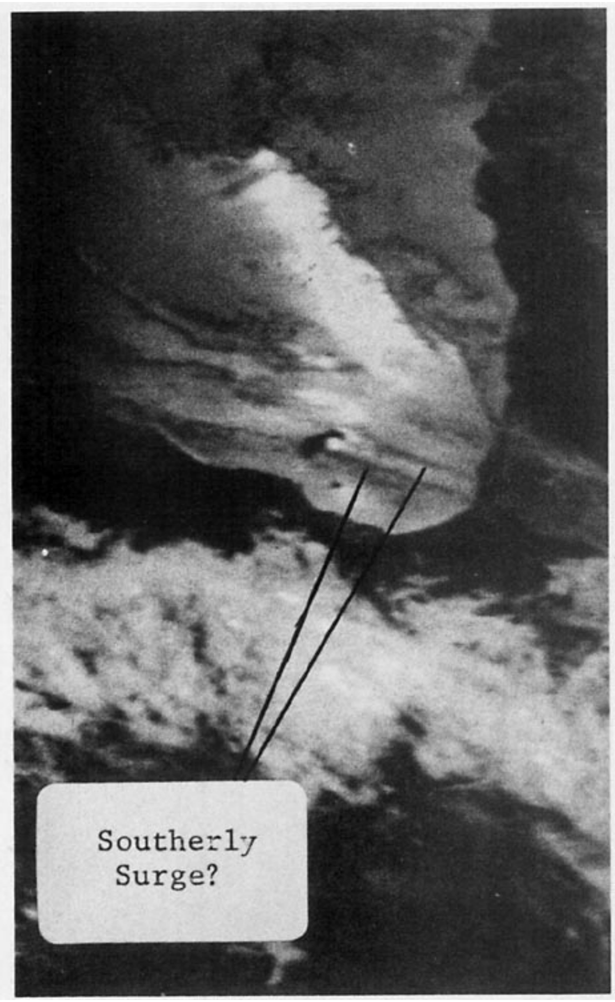


FIG. 2. Visible satellite imagery of the Gulf of Carpentaria region at 1000 EST (00 GMT) on 6 November 1980 showing cloud lines probably associated with a southerly surge.

and to the relatively weak disturbances of the twenty-first and fifteenth, the latter being distinctly more undular than the former. (Henceforth, where no ambiguity of month or year arises, we refer to surge occurrences by their day-date alone.) It is of course impossible with these single station data to know whether the surges were intrinsically different in character, or whether they passed over the station at different stages in their evolution. It may be significant that for the case of the twelfth, the trace takes on a more undular character when an attempt is made to remove the component of the pressure rise attributable to the average semidiurnal variation at the relevant time of day. (See Smith et al., 1982; their Fig. 11.) Removal of the atmospheric tide component from pressure time series is a difficult procedure, for the reasons given in Smith and Morton (1984, p. 168), and we have not attempted it for the traces in Fig. 5. However, an estimate of the semidiurnal rise in pressure over the southern Gulf of Carpentaria region during October between 0600 and 0900, the period when disturbances are most commonly observed passing through the region, shows it to be of the order of 0.2 mb $h^{-1}$. This is based on three-hourly synoptic data from Normanton, which is at almost the same latitude and, in terms of the phase of the semidiurnal wave, only a few minutes ahead of Burketown (Fig. 1). The pressure rise during each event in Fig. 5 exceeds this value over the full extent of the trace measured from the time of the initial sustained rise. This is at least consistent with the suggestion that southerly surges have a bore-like structure similar to their northeasterly counterparts, in contrast to a wave-like structure where, following the disturbance passage, there is a return to conditions prevailing before the onset.

Further important evidence for a bore-like structure is the relative streamline patterns; these are shown in

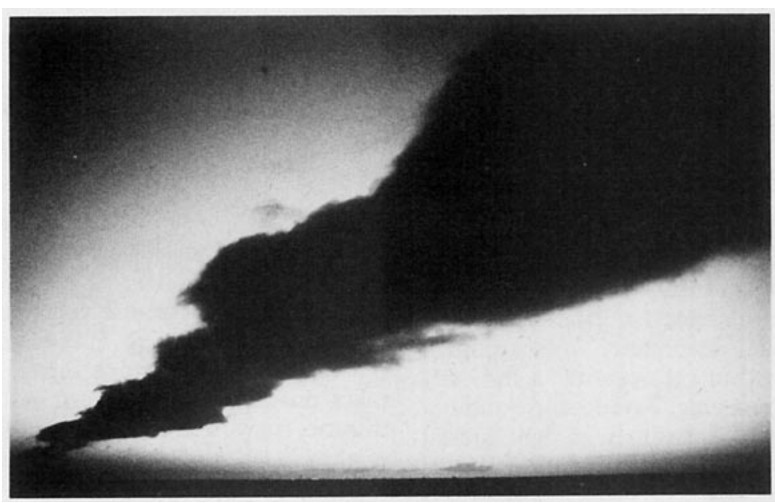

FIG. 3. View, looking eastward, of the southerly morning glory cloud line of 21 October 1981. The photograph was taken a few kilometers east of Burketown at about 0545.

FIG. 4. A rare photograph of a northeasterly morning glory cloud line (left) interacting with a weaker disturbance from the south. The picture was taken some time between 0600 and 0800 on 18 September 1982 from the Burketown School, looking southeast. (Courtesy of Mr. B. O'Brien.)

Fig. 6 for three of the surges represented in Fig. 5. The streamlines are calculated as the vertical integral of the low-level wind component in the direction from which the surge arrives, measured relative to the motion of the surge. The speed and direction of surges were determined from surface network data. Details of the streamfunction calculation are given in Smith and Morton (1984, appendix A). However, it should be noted that the calculations herein were performed on the assumption that vertical air motion was everywhere small compared with the balloon ascent rate of 2.2 m $s^{-1}$. This assumption was valid in the majority of soundings used for Fig. 6, especially the important ones well ahead of and far behind the leading edge of the surge. Also, it is assumed that transverse variations within the surge are small and that the structure is sufficiently stationary in time that a time-to-distance conversion is appropriate to determine the horizontal scale of the streamlines. The details of the streamline patterns are necessarily schematic, since individual waves were in no cases adequately sampled by balloons and were mostly not sampled at all. Indeed, the presence and form of individual waves had to be inferred from the surface pressure signature, in combination with surface

TABLE 1. A summary of data available on southerly surges. Note the occurrence of several significant events in the late evening/early morning of 21–22 Oct 1981. Times refer to the time of passage at Burketown and are in Australian eastern standard time (=GMT + 10 h).

| Event | | | | Data available | | | | |
|---|---|---|---|---|---|---|---|---|
| Date | Time (EST) | Speed ($m\ s^{-1}$) | Direction (deg) | Sapix | Temperature sounding | Upper winds | Anemograph network | Cloud observation |
| 6 Oct 1979 | 0700 | >15 | 180 ± 20 | yes | no | no | no | yes |
| 9 Oct 1980 | 0638 | ≤15 | 165 ± 15 | no | no | yes | no | yes |
| 12 Oct 1980 | 0712 | ≤17 | 170 ± 15 | no | no | yes | no | yes |
| 6 Nov 1980 | unknown | unknown | 180 ± 20 | yes | no | no | no | no |
| 19 Oct 1981 | 0305 | 11.4 ± 0.3* | 224 ± 3* | no | no | no | partial | no |
| 21 Oct 1981 | 0540 | 7.9 ± 0.5* | 150 ± 5* | no | yes | yes | partial | yes |
| 22 Oct 1981 | 2245/21 Oct<br>2348/21 Oct<br>0050 | 14.5 ± 2.9*<br>9.7 ± 0.3*<br>unknown | 249 ± 7*<br>139 ± 1*<br>unknown | no | no | no | partial | yes |
| 18 Sep 1982 | 0730 | unknown | 180 ± 20 | no | no | no | no | yes |
| 15 Oct 1982 | 0641 | 13.0 ± 1.0 | 158 ± 5 | no | yes | yes | yes | no |
| 20 Oct 1982 | 0929 | 12.4 ± 0.3* | 218 ± 3* | no | yes | yes | yes | no |
| 9 Sep 1983 | 0530 | 12.3 ± 1.0 | 185 ± 5 | no | no | no | yes | no |
| 15 Sep 1983 | 0500 | 6.1 ± 1.0 | 220 ± 5 | no | no | no | yes | no |
| 25 Oct 1984 | 0510 | unknown | unknown | no | yes | yes | yes | yes |
| 26 Oct 1984 | 0205 | 17.4 ± 0.4 | 204 ± 2 | no | no | no | yes | yes |

* Data kindly provided by D. R. Christie.

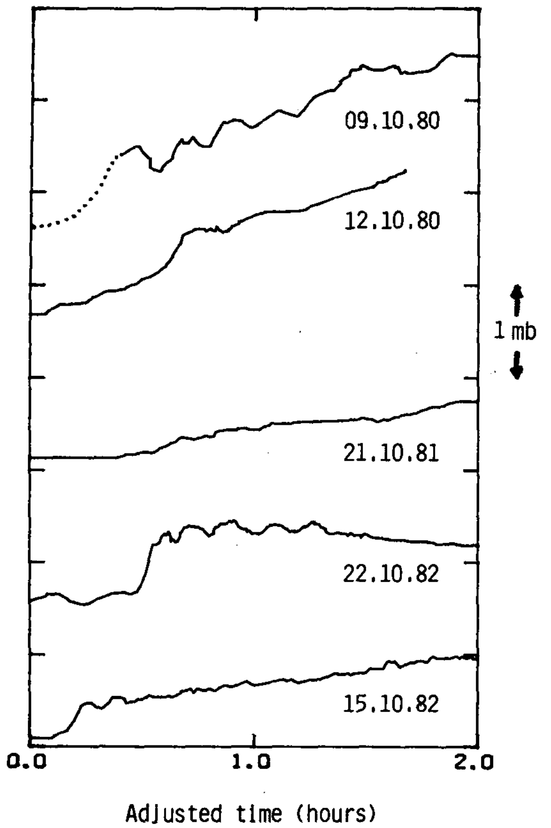


FIG. 5. Time series showing the variation of surface pressure for five southerly surges (dates are shown). Tick marks on the ordinate are at 1 mb intervals. The broken line indicates a data gap. No significance other than date attached to the position of curves in the vertical.

wind data and/or the presence of cloud lines. Their amplitude could not be related to the amplitude of waves in the surface pressure trace (cf. Noonan and Smith, 1985) and must be regarded as uncertain. Despite these limitations, the streamline patterns for each case show unequivocally an increase in mean streamline height following the passage of the surge, and at all positions sampled by balloons the relative flow is in the downstream direction. This confirms the essentially bore-like nature of surges. The qualification "essentially" is necessary here and will be discussed subsequently.

The low-level wind components along the line of propagation of the surge, and at right angles to it, are shown in Fig. 7 for the few events for which such data are available. It is significant that, in general, there is no pronounced low-level flow (up to 500 m) towards the surge, as is commonly the case for northeasterly surges (Smith and Morton, 1984); neither is there much in common between cases in the normal or transverse components. A nocturnal low-level jet is apparent on the twelfth, fifteenth and twenty-first, but in the first two of these cases it is largely transverse to the surge while in the last case it is approximately in the surge direction. These profiles are suggestive that the occurrence of a southerly surge at Burketown is *not* determined by the local winds. This is contrary to data for northeasterly surges for which a precursor is invariably a weak westerly component in the lowest few hundred meters (Clarke et al., 1981; Smith and Morton, 1984); it would seem to suggest that the latter is fortuitous and not essential to bore formation.

The presurge thermal structure, characterized by the vertical profile of virtual potential temperature $\theta_v(z)$ is shown in Fig. 8 for the surges of the twenty-first (1981), fifteenth (1982), twentieth (1982) and twenty-fifth (1984). All were made early in the morning, three of

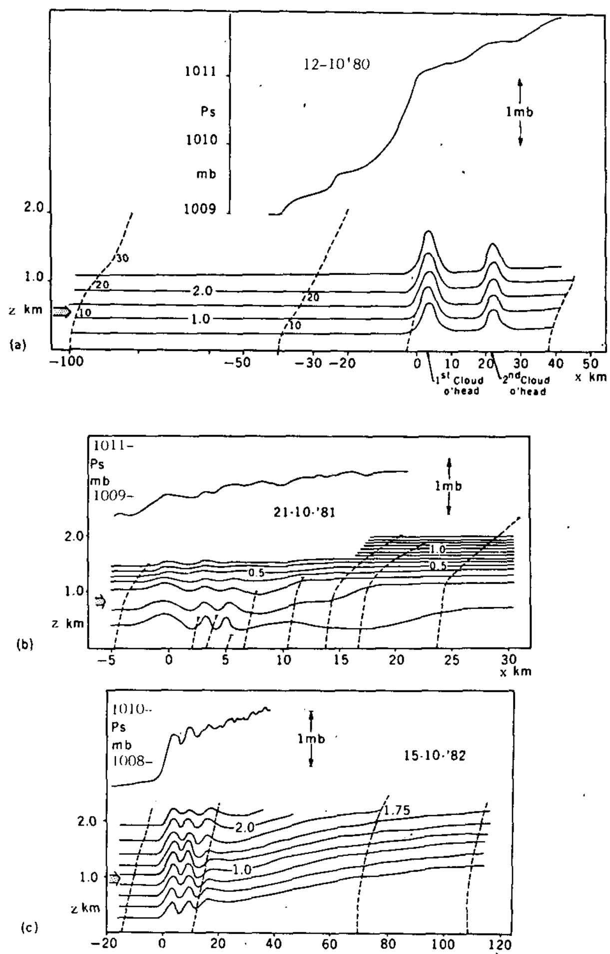


FIG. 6. Time–height cross sections of streamlines relative to the motion of the pressure jump in a plane normal to the pressure jump line at the surface for three southerly surges. Streamlines are labelled in units of $10^4$ $m^2$ $s^{-1}$. Vertical broken lines denote relative balloon trajectories in the plane. The position of waves is inferred, as far as possible, from the pressure time series included above each streamline pattern, and especially in panels (a) and (c) wave structure must be regarded as schematic. The abscissa scale is given in units of distance from the pressure jump line using the observed speed of propagation of the line to effect the time-to-distance conversion.

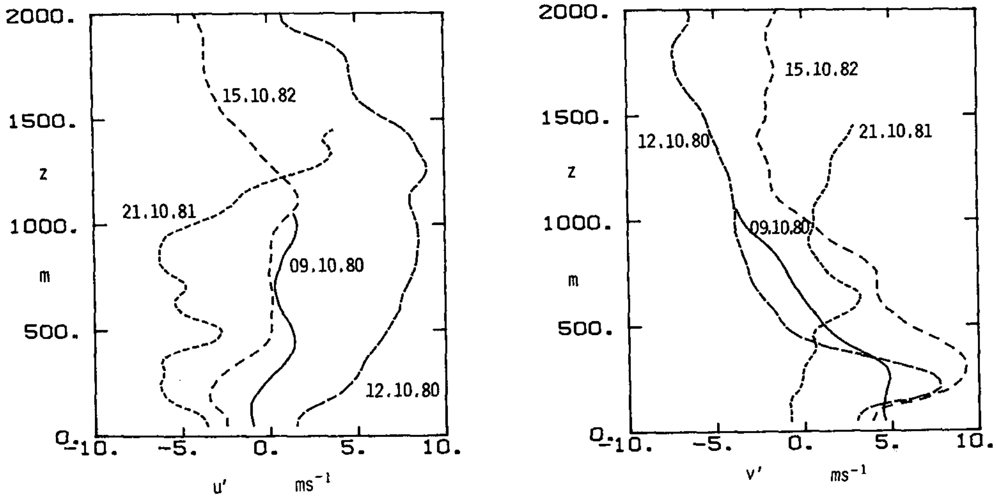


FIG. 7. Vertical profiles of wind components normal to ($u'$), and parallel with ($v'$) the surface pressure jump line ahead of four southerly surges. (Dates as indicated.) Here $u'$ is positive in the direction *from which* the surge arrives and $v'$ is positive to the left of this direction.

them less than an hour before the passage of the surge and the other, on the twentieth, about three hours before. The soundings on the fifteenth, twentieth, and twenty-fifth show similar features, the most prominent being the strongly stable layer in the lowest few hundred meters and the overlying near-neutral layer, a remnant of the well-mixed layer of the previous day. In the case of the twenty-first, the strongly stable layer is absent, but the layer of marked stability is deeper than the others; on this day the overlying near-neutral layer would most likely have been present, but was not sampled. These profiles are similar to those ahead of northeasterly surges and are typical of early morning soundings at Burketown in October.

Of particular interest is the comparison of pre- and postsoundings of $\theta_v(z)$, which are available only for the events of the twenty-first and twenty-fifth; these are shown in Fig. 9. In each case a slight cooling (1–3°C) is apparent in the lowest one thousand to fifteen hundred meters, a finding consistent with similar data for northeasterly surges (Smith and Morton, 1984, Fig. 21; Smith and Page, 1985). This is not in conflict with the interpretation of the surge as an undular bore, but is consistent with a gravity current origin of surges. We elaborate on this in section 5.

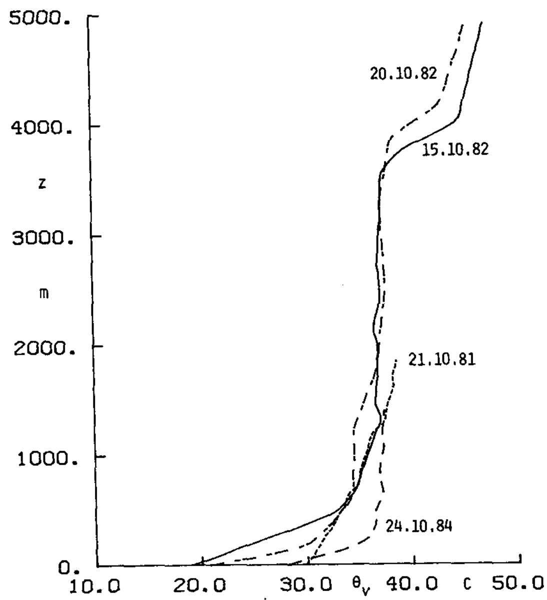


FIG. 8. Vertical profiles of virtual potential temperature ahead of four southerly surges. (Dates are indicated.)

## 4. Synoptic conditions for southerly surges

In section 3 it was shown that southerly surges, like their northeasterly counterparts, are relatively shallow phenomena confined predominantly to the lowest few kilometers of the atmosphere. On this account we are led to explore synoptic conditions at the surface conducive to their formation. In the relatively sparse data region of northern Australia, mean sea level isobaric charts provide a more adequate definition of the broadscale flow than, say, gradient wind charts.

Figure 10 shows the 0900 surface charts for the surge days in 1979 and 1980 listed in Table 1 and for the day before. The synoptic situation for the events of the sixth (1979), twelfth, and sixth (1980) are quite similar: on the day prior to the surge, there was strong ridging across the center of the continent from the semipermanent Indian Ocean anticyclone, following the passage of a frontal trough. On the eleventh and fifth (1980), the front is truncated at 26°S with the associated low centered about 38°S, whereas on the fifth (1979) the low center is well south of the continent and the

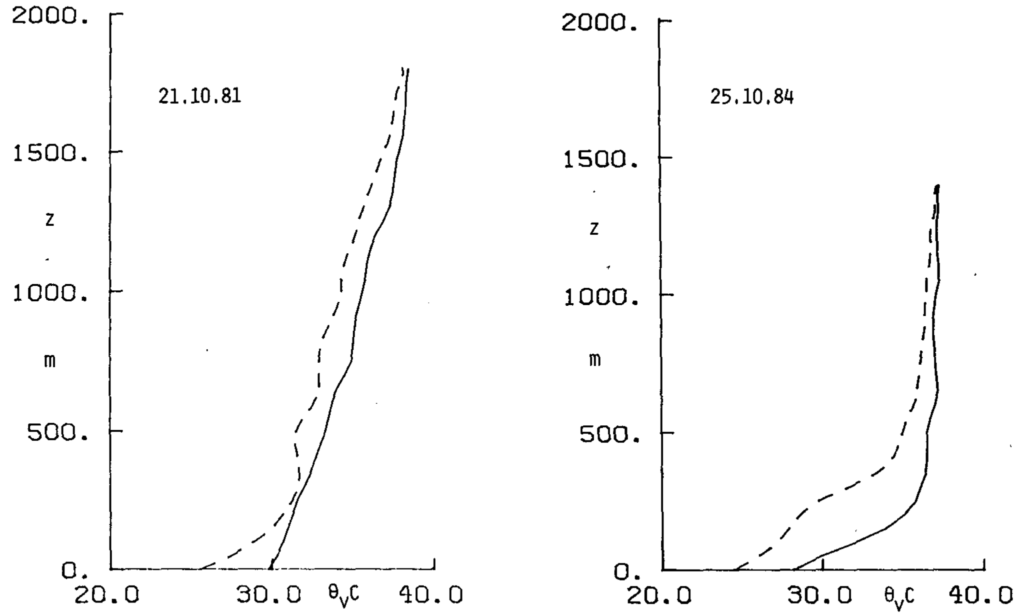


FIG. 9. Vertical profiles of virtual potential temperature ahead of and behind the southerly surges of (a) 21 October 1981, and (b) 25 October 1984. Both profiles show cooling following the passage of the surge.

front is drawn equatorwards only to about 29°S. Twenty-four hours later, and in each case some two or three hours after the surge passage through Burketown, the trough had moved eastwards and the surface front is no longer drawn, since surface pressure, wind, and temperature discontinuities are no longer discernible. In each case, also, pressure gradients across northwest Queensland and the gulf were slack, although a weak trough with its axis orientated approximately north-west–southeast is discernible. Note that the isobars in Fig. 10 are only every 4 mb; more detailed regional analyses for the twelfth are shown in section 5. Also, it should be pointed out that the charts are somewhat schematic and the precise positioning of fronts may be dependent on the particular analyst.

On the eighth/ninth the synoptic situation was a little different from the others; on the eighth an anticyclone was centered near Adelaide (34°56′S, 138°35′E) and a ridge extended to the north. During the subsequent 24 hours, this anticyclone moved east-southeastwards and pressures fell over central Australia. Like the other days, there was a quasi-stationary heat trough across northern and eastern Queensland, a quasi-permanent feature at this time of year, but the moving frontal trough to the south was absent.

The synoptic conditions for other surges listed in Table 1 are shown in Figs. 11–13. For the five day period 18–22 October 1981 the isobaric patterns are in many respects similar to those of the common three described previously. Between the eighteenth and nineteenth, the Indian Ocean anticyclone extended a ridge across central Australia towards the quasi-stationary heat trough across Queensland, while a cold front ahead of the ridge on the eighteenth slipped away to the south of a blocking anticyclone in the Tasman Sea. Continued eastward movement of the high in the Great Australian Bight was suppressed by the formation of a complex low-pressure system over eastern New South Wales on the twentieth, and for the following 24 hours the situation over northwest Queensland remained broadly static. Ridging over the central and eastern part of the continent continued between the twenty-first and twenty-second as the low pressure region moved into the Tasman Sea to reinforce the blocking system there.

The situations shown in Figs. 12 and 13 for surges documented in 1982–1984 again show the eastward/northeastward ridging across central Australia on days prior to surge days with cold fronts ahead of the ridges lying generally poleward of 27°S. The one exception is that of the fourteenth/fifteenth (1982), where the pressure pattern over the continent remained more or less stationary, but with essentially the same configuration as for the other periods.

It is interesting that on the nineteenth and twentieth (1981), the seventeenth and nineteenth (1982) and the twenty-fourth (1984), conditions were especially favorable for the formation of northeasterly surges with a ridge of high pressure along the east coast of Queensland directing geostrophic easterly to northeasterly winds across Cape York Peninsula (Clarke et al., 1981). Moreover, northeasterly as well as southerly surges *were* observed on these days (Clarke, 1983x; Smith and Morton, 1984).

The eastward movement of a frontal trough through Mount Isa during the 12 hours prior to the southerly

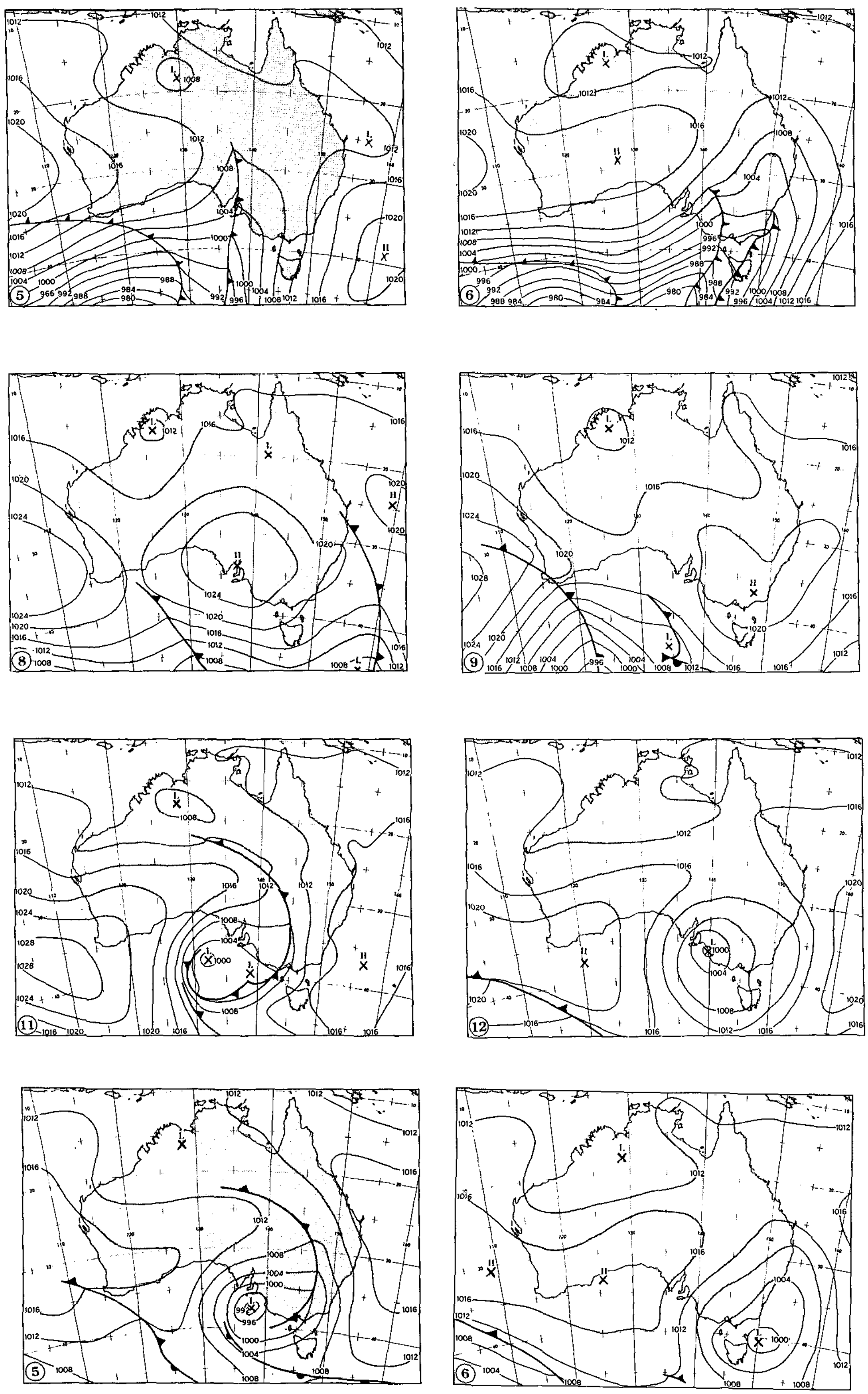

FIG. 10. Bureau of Meteorology Australian region near sea level isobaric analysis for 0900 on (a) 5 and **6** October 1979; (b) 8 and **9** October 1980; (c) 11 and **12** October 1980; and (d) 5 and **6** November 1980. Days on which surges occurred at Burketown are denoted by bold type.

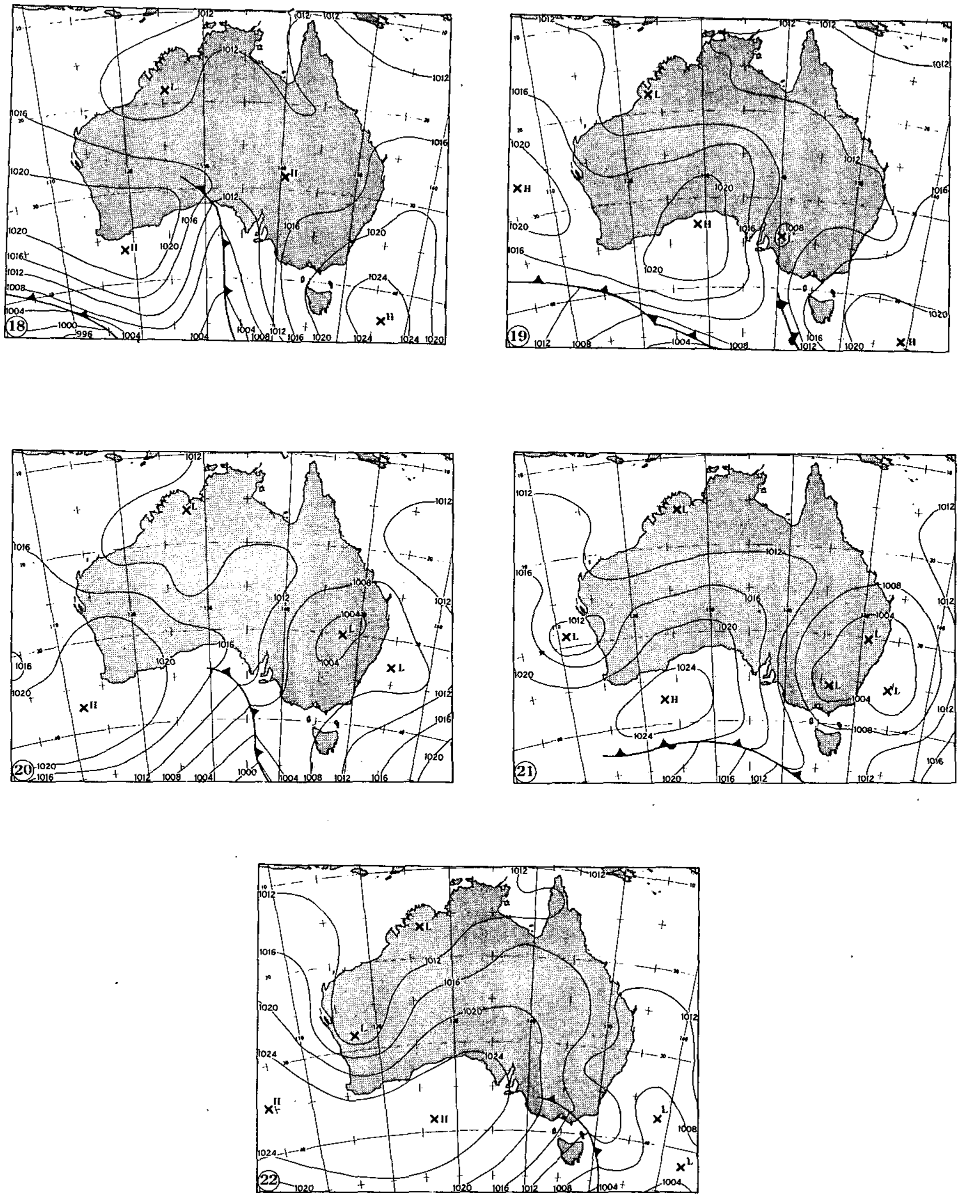

FIG. 11. As in Fig. 10, except for 18, 19, 20, 21 and 22 October 1981.

surges of the sixth (1979) and twelfth was noted by Smith et al. (1982). The trough movement and strong ridging that followed was evidenced by a phase lag in time series of 24 h isallobars at Alice Springs (24°S, 133°E) and Mount Isa (20°S, 140°E), computed every three hours. No signature was found in the isallobars for the ninth that was consistent with the isobaric patterns on the eighth and ninth shown in Fig. 10. The relatively static situation for this event is mirrored by those on the nineteenth–twenty-first (1981) and fifteenth (1982). From this we may infer that while strong ridging across central Australia following the passage of a frontal trough may be conducive to the formation of southerly surges, the presence of a quasi-stationary high pressure region centered in the vicinity of the Great Australian Bight, with a southeasterly airstream over central Australia and a heat trough across northwest Queensland, may be sufficient.

Further precursors of southerly surges were sought in time series of six-hourly low-level winds at Mount Isa, the closest upper air station to Burketown. We characterize these winds by the arithmetic mean of the 950 mb and 900 mb wind components, time series of which are shown in Fig. 14 for the periods 2–9 October 1979, 7–14 October 1980 and 15–22 October 1981. A prominent feature of these time series is the frequent

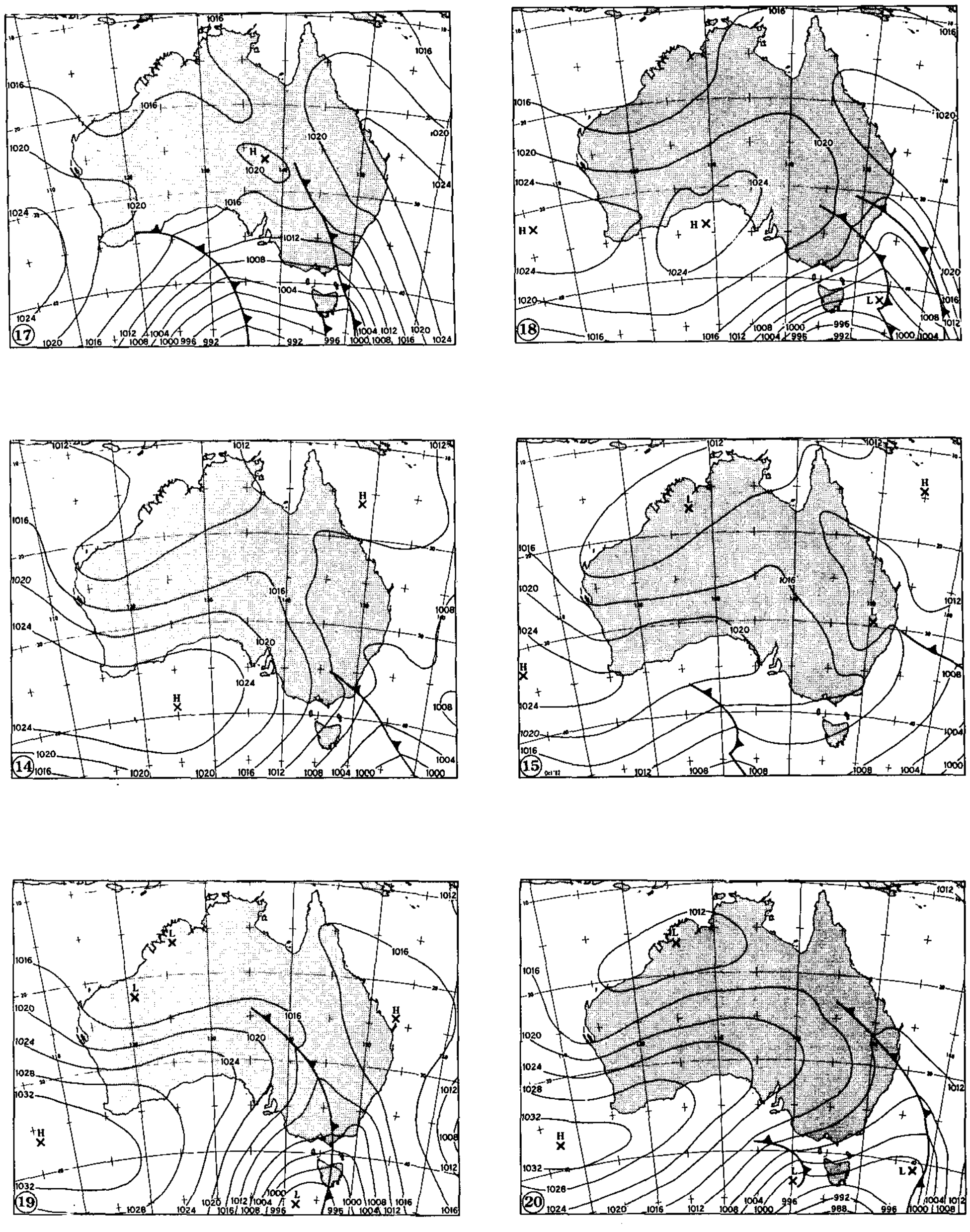


FIG. 12. As in Fig. 10, except for (a) 17 and **18** October 1982, (b) 14 and **15** October 1982, and (c) 19 and **20** October 1982.

occurrence of a sharp increase in the southerly component during the late evening and early morning (2100–0300 and occasionally between 1500 and 0300), followed by or concurrent with (at six-hour resolution) a sharp rise in the easterly component. What is striking is that this feature, which we shall refer to as the Isa wind signature, is often more pronounced on occasions when southerly surges are observed in Burketown, generally between 0500 and 0800. It stands out clearly on the sixth (1979), ninth and nineteenth–twenty-first (1981), but to a much lesser extent on the twelfth. On the other hand, it is present on a few other occasions when no obvious southerly surges were detected at Burketown; for example, on the eighth (1980) the signature is present, but occurs later—between 0300 and 1500. Data for seven other week-long periods—one in November 1980 and the others during 1982–1984—are summarized in Table 2. In brief, these concur with the data presented above; the Isa wind signature is striking for the surges of the sixth (1980), twentieth (1982) and ninth and fifteenth (1983); it is less pronounced for the surge of the twenty-sixth (1984), and is not a well-defined feature for those of the fifteenth (1982) or twenty-fifth (1984). Moreover, there were

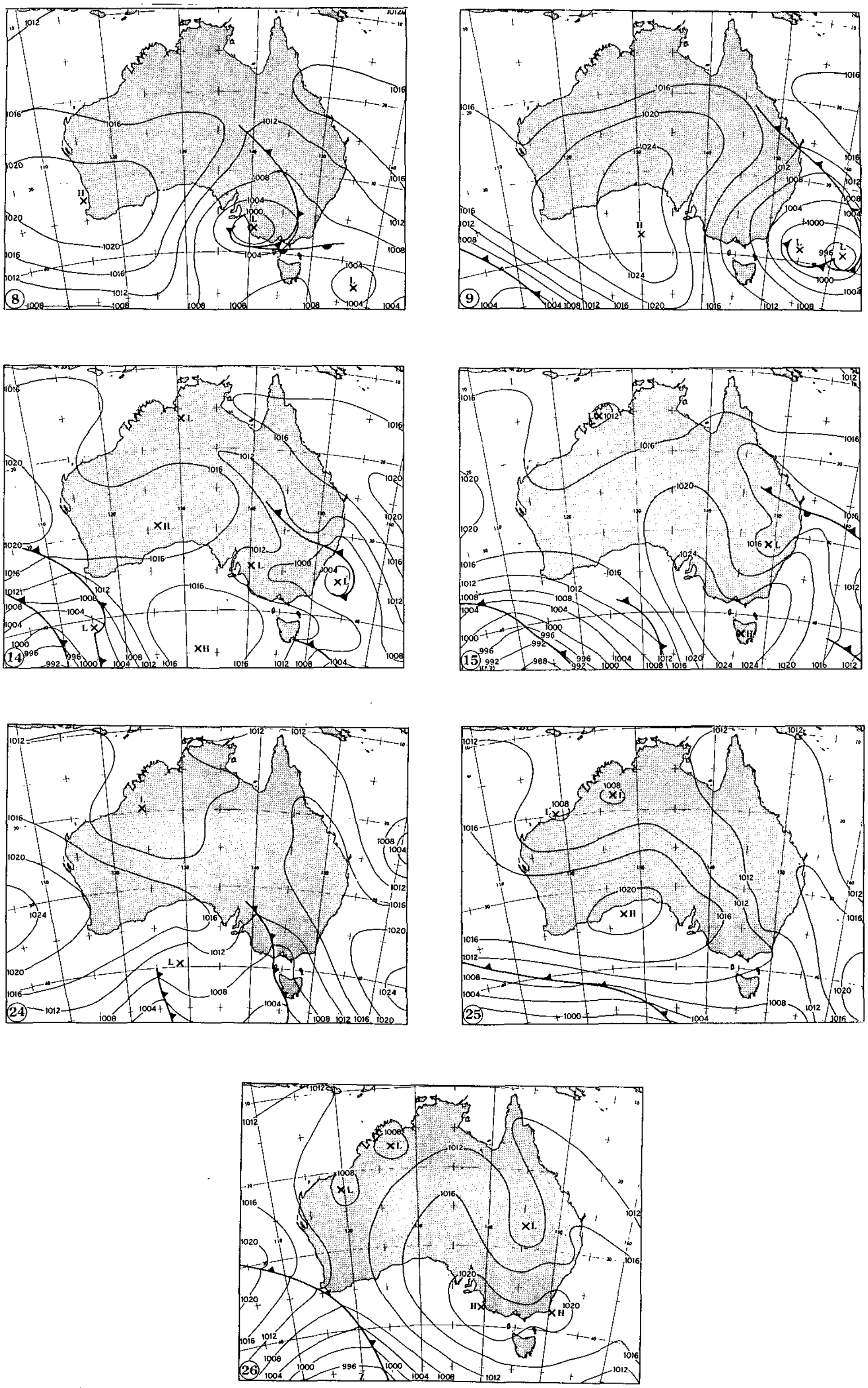


FIG. 13. As in Fig. 10, except for (a) 8 and **9** September 1983; (b) 14 and **15** September 1983; and (c) 24, **25** and **26** October 1984.

TABLE 2.

| Year | Period | Days of Mount Isa signatures | Days of confirmed southerly surges |
|---|---|---|---|
| 1979 | 2–08 Oct | 5/6 | 6 |
| 1980 | 7–13 Oct | 7/8, 8/9, 11/12*, 12/13 | 9, 12 |
| | 2–08 Nov | 2/3, 5/6, 6/7, 7/8, 8/9 | 6 |
| 1981 | 15–21 Oct | 15/16, 16/17, 17/18, 19/20, 20/21, 21/22 | 16, 17, 18, 20, 21, 22 |
| 1982 | 15–21 Sep | none on 17/18 no others, but some data loss | 18 |
| | 14–20 Oct | 19/20 | 15, 20 |
| 1983 | 8–14 Sep | 8/9, 14/15 | 9, 15 |
| 1984 | 21–26 Oct | 21/22, 25/26* | 25, 26 |

* Weak signature.

days also during these periods when a pronounced signature was evident, but no surge was detected at Burketown.

While the foregoing data may not be regarded as conclusive evidence for an association between the Isa wind signature and the occurrence of southerly surges, we believe the evidence is sufficiently strong to merit presentation. This view is strengthened by the fact that on occasions when there was a pronounced signature at Mount Isa and the surface data were sufficiently good, evidence of a southerly surge could usually be found. For example, in 1981, the Isa wind signatures of the fifteenth/sixteenth, sixteenth/seventeenth and seventeenth/eighteenth were followed on the sixteenth, seventeenth and eighteenth, respectively, by significant wave disturbances in the Burketown region originating from the south (D. R. Christie, personal communication, 1985). Data for days other than the ninth (1983) and fifteenth (1983) from the surface anemograph network are difficult to interpret conclusively without simultaneous detailed surface pressure data.

## 5. Origin of southerly surges

At this stage the data are inadequate to determine the precise mechanism (or mechanisms) of surge formation, but some inferences are possible from the analyses presented above. One scenario, suggested by Smith et al. (1982, section 4) is that the northeastward advance of a frontal trough across central Australia is retarded by the enhanced intensity of the semi-permanent heat trough during the daytime in the area just south of the Gulf. In the late afternoon and early evening, the heat trough weakens and the frontal trough accelerates into a developing nocturnal inversion, generating a bore-like disturbance which propagates along the inversion, in much the same way as envisaged by Tepper (1950). Smith et al. (1982) describe a laboratory experiment which demonstrates the efficacy of this type of mechanism; they note also that with the existence of a preferred location for the daytime heat trough south of the gulf (see, e.g., Figs. 10–13), the preferred time of day for the acceleration of the frontal trough might explain why southerly surges often reach the Gulf coast between about 0500 and 0800. The possible role of a moving frontal trough was noted by Christie et al. (1981) and that of the heat trough by Clarke (1983b). However, the synoptic analyses of section 3 show that the passage of a frontal trough across central Australia is not always a precursor to southerly surge occurrences. For example, during the period 19–21 October 1981, southerly surges occurred each day, while the synoptic pattern remained more or less stationary with no obvious frontal trough present; neither was a frontal trough in evidence on the eighth–ninth (1980) and fourteenth–fifteenth (1982). It was this fact which led us to seek clues in the low-level winds at Mount Isa, where on each day during the period 19–21 October 1981 there was a pronounced wind signature as described in section 4. The marked strengthening of the southerly component between 1500 and 0300[2], followed by the strengthening of the easterly component between 2100 and 0900[2] (Fig. 14), is indicative of the formation of a strong nocturnal jet in the Mount Isa region and it is conceivable that this could play a central role in the formation of southerly surges. In this regard, note that Mount Isa lies 340 m above mean sea level, while the 950 and 900 mb geopotential surfaces are nominally about 500 and 1000 m above sea level, respectively. Hence, the arithmetic mean of the 950 and 900 mb winds can be expected to capture the nocturnal jet, the axis of which is a few hundred meters high in this region (cf. Garratt, 1985).

Clarke (1983b, p. 159) notes that the presence of a trough lying northwest–southeast in the vicinity of the Gulf Coast would be associated with shallow northerly winds on its northeast side. These are conducive to a deeply penetrating sea breeze along the southern gulf coast which lays down a stable layer of cool air along a coastal strip during the afternoon and evening. The deep inland penetration of sea breezes in this region has been well documented. (See, e.g., Clarke et al., 1981; Clarke, 1983a, 1984; Garratt and Physick, 1985; Physick and Smith, 1985.) Above the sea breeze is normally a deep well-mixed layer of continental air, capped by an inversion at about 4 km (Fig. 8). The low-level stable layer, which is strengthened overnight by radiative cooling, together with the overlying adiabatic layer, provides an effective wave guide for any disturbances that are generated. It is clear that the development over the land of a nocturnal jet with a southerly component

[2] The reader is reminded of the coarse time resolution in the upper wind data.

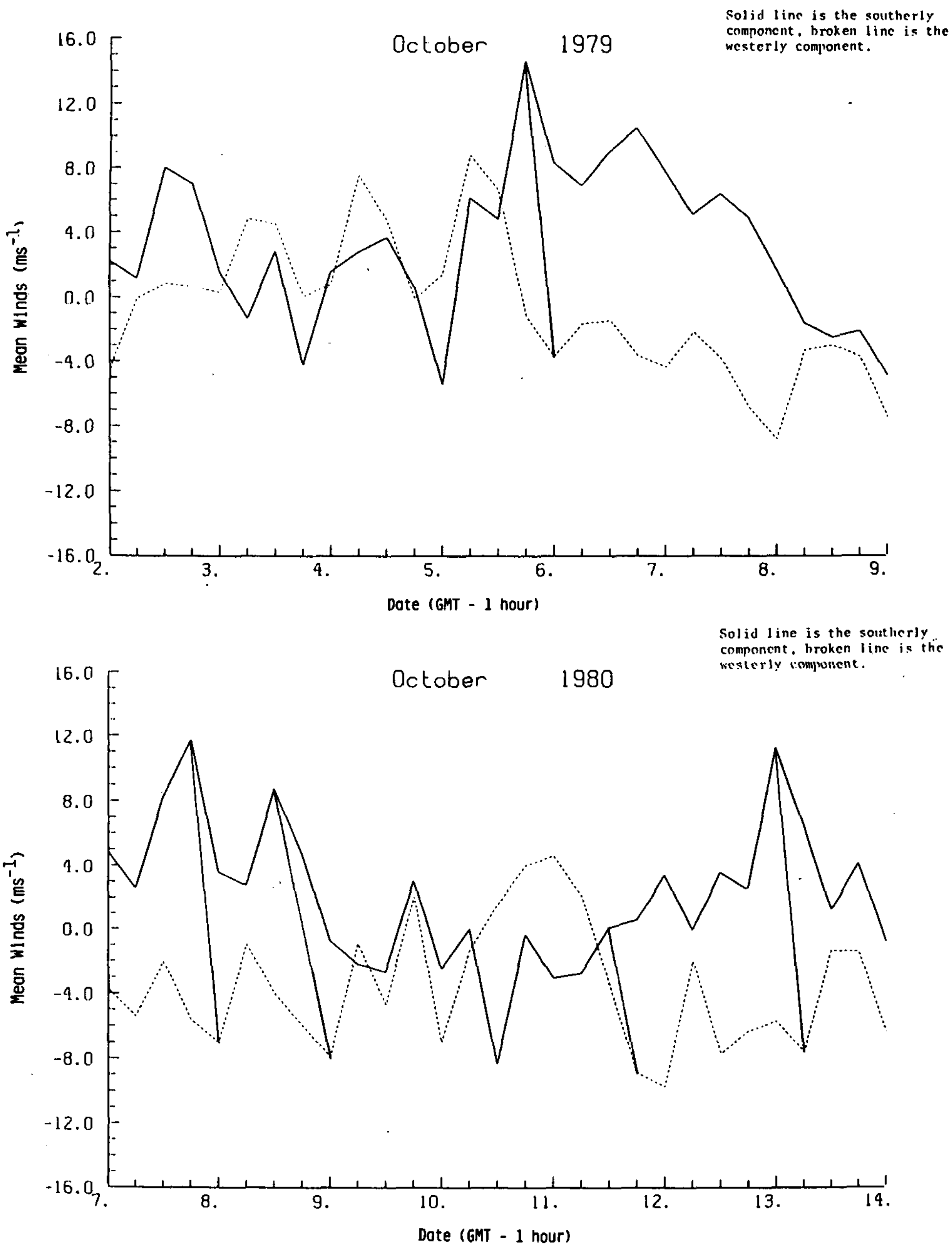


FIG. 14. Time series of six hourly mean wind components (the average of the archived 950 and 900 mb wind components) for Mount Isa for the seven-day period commencing at 0900 (0000GMT—1 hour) on (a) 2 October 1979, (b) 7 October 1980, and (c) 15 October 1981. Solid line is the southerly component, broken line is the westerly component.

southwest of the inland trough, combined with northerly winds ahead of the trough, would lead to convergence in the trough during the evening. If the jet is strong enough, it would seem capable of generating a bore-like disturbance which propagates northwards on the low-level stable layer, in much the same way that convergence of the east and west coast sea breezes over Cape York Peninsula is known to lead to the generation of northeasterly surges. Regrettably, the available data are not adequate to test the details of this hypothesis, but studies are being carried out using a mesoscale numerical model to make an assessment of the envisaged mechanism.

The role of katabatic drainage in the production of northeasterly surges was explored by Clarke (1972), and while it is believed now that this is not the main cause of surges, it cannot be ruled out as a contributory effect (Clarke et al., 1981; Clarke, 1983b). Likewise,

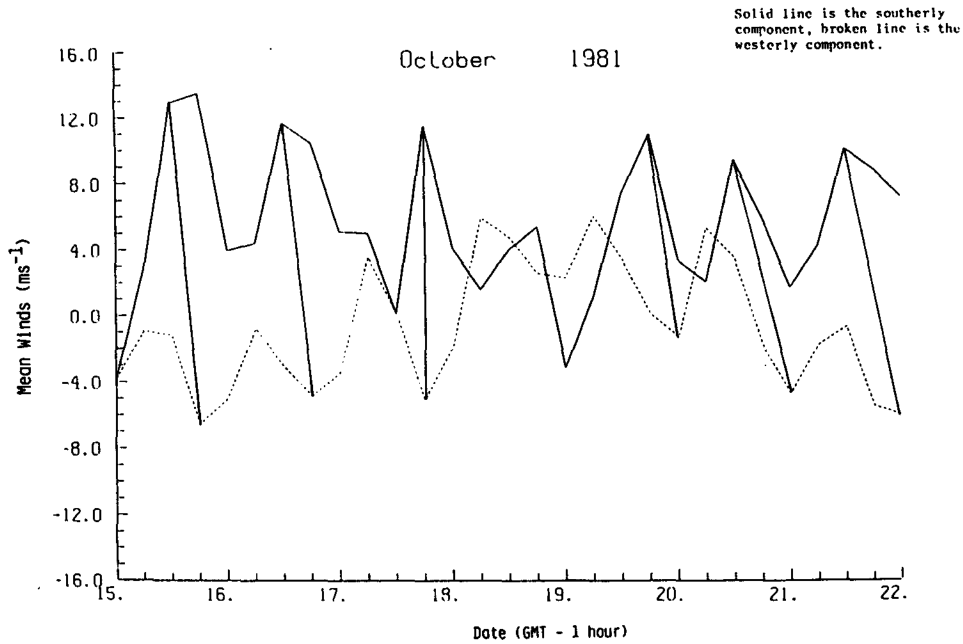


FIG. 14. (*Continued*)

we cannot rule out the possibility that katabatic drainage from the Barkly Tablelands is responsible for southerly surges, or at least a contributory effect in their generation. Recall that Mount Isa is 340 km south of the Gulf Coast and is about 340 m above near sea level, giving a mean slope on the order of 1 in 1000 to the coast. This is similar to the mean slope on the western side of Cape York Peninsula. It will be recalled that on one or two occasions (e.g., 18 September and 15 October 1982), the southerly surge at Burketown was not preceded by either a significant wind signature at Mount Isa, or the passage of a frontal trough across central Australia. It is possible that katabatic drainage could have played a major role in the generation of these surges. However, it should be remembered that Mount Isa *is* a considerable distance from Burketown (~340 km) and the upper winds there may not be typical always of the conditions between Mount Isa and the Gulf Coast. Again, in the absence of adequate data, studies are in progress to assess the efficacy of katabatic drainage as a generation mechanism for southerly surges using a numerical model.

It is by no means inconceivable that *all* the mechanisms described above could be the leading mechanism in particular cases. Laboratory experiments are suggestive that for wave-guide structures such as the one described herein, disturbances with the structure of southerly surges evolve from quite general initial conditions. (See in particular Maxworthy, 1980, p. 52; Christie and Muirhead, 1983; Smith and Morton, 1984, p. 158.)

Finally, we consider the observed cooling following surge passages as indicated in Fig. 9, and its implication regarding our interpretation of the surge structure as an undular bore. Recent laboratory experiments by Wood and Simpson (1984) appear to be of particular relevance to the problem at hand. In these experiments, a gravity current was studied as it advanced in a two layer fluid, the lower layer with depth $d$ having the same density as the advancing fluid. When $d = 0$ the motion is that of a pure gravity current, with a low-level feeder flow behind the head, rising motion at the head itself and a return flow (relative to the speed of the head) aloft (Simpson, 1982). However, as $d$ increases, the head becomes undular and the flow progressively takes on the structure of an undular bore. The waves comprising the head become more and more like discrete entities with approximately closed cells of recirculating dense fluid; the density becomes progressively reduced by turbulent mixing as the flow evolves. The precise relationship between these types of waves and large amplitude internal solitary waves has not been established, but locally one would expect their structure to be very similar. In particular, both types are accompanied by some advected fluid.

The observation of cooling following the passage of a southerly surge is suggestive of its origin as some form of gravity current, whether it be surface based or internal, as it might be if associated with the inland nocturnal jet. The experiments of Wood and Simpson (1984) show that the observed undular bore-like structure determined at Burketown is not inconsistent with such an origin. More importantly, the experiments show that the surge *need not* develop ahead of the gravity current itself, as happens in the experiments performed by Smith et al. (1982), but may be associated with an evolution in structure of the gravity current itself.

## 6. Implications for synoptic analysis and forecasting

Synoptic analysis over northeast Australia south of the Gulf of Carpentaria is particularly difficult during the transition period from the dry winter season to the wet summer season when morning glory-type surges are most frequent. This is due not only to the relatively few reporting stations and infrequent reports (some stations report only twice daily, typically at 0900 and 1500), but also to a number of meteorological factors, including the presence of morning glory-type surges which may confuse an analyst unfamiliar with this kind of disturbance. We conclude with a brief summary of some of the difficulties, illustrating this with a particular case where a southerly surge was present.

During the transition to the summer monsoon season there is a strong diurnal heating cycle. This causes a waxing and waning of the semi-permanent low pressure trough across the region inland from the gulf, and to a diurnal cycle in surface winds, with vigorous mixing of gradient winds down to the surface during the day and a calm, surface-based stable layer at night, frequently capped by a strong nocturnal jet. A marked semi-diurnal atmospheric tide is present also. The intrusion of the sea breeze from the gulf leads to the establishment of moisture discontinuities or, roughly, northwest/southeast "dry lines"; these may persist, but fluctuate in location depending on the existence and intensity of a subtropical ridge to the south. Typically too, low pressure troughs associated with transient weather systems to the south move through or into the area. The prediction of thunderstorm activity in these troughs is probably the major forecasting problem of the region at this time of the year. Finally, morning glory wind surges are associated with sharp pressure rises and strong but transient wind squalls at their leading edge, and may be reported, as "discons" to further complicate the analysis. These surges may trigger deep convection also, and even thunderstorms, as they move into moister air over the gulf, irrespective of the time of day.

An appreciation of the difficulties of analysis can be gained by an examination of a series of mean sea level pressure charts encompassing the southerly disturbance of the twelfth (1980), an event which seems to have been associated with the passage of a major weather system well to the south.

The general broadscale pattern for this event (Fig. 10) is described in section 4. Here we focus on the regional analyses for the synoptic hours of 0300, 0600 and 0900 on the twelfth (Fig. 15). Isobars have been drawn at 1 mb intervals to identify the patterns and features more clearly, but the data base is that which was available to forecasters at the time. At 0300 we have drawn three dashed lines (Fig. 15a). The northernmost line signifies the approximate location of the dry line formed by the previous day's sea breeze. The next line south marks the trough line which had been reported as a pressure and wind discontinuity passing through Mount Isa at 2020 the night before. The southernmost line marks the limit of the cooler air circulating anticlockwise around the ridge. A weak low pressure cell lies over the area to the south of the Gulf. On the 0600 analysis (Fig. 15b) the ridge has intensified with the cooler air penetrating further north, but the

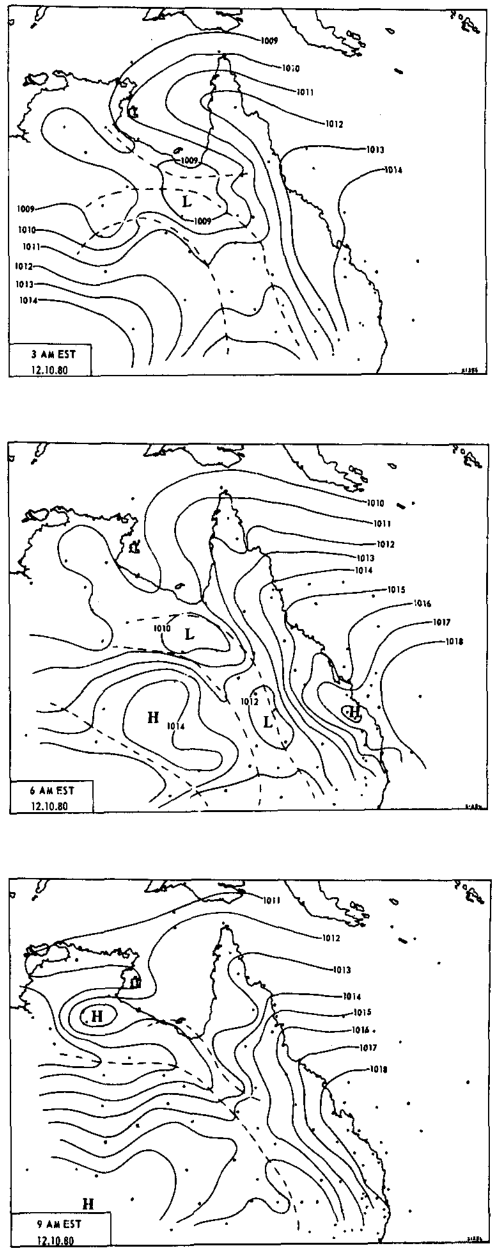


FIG. 15. Reanalyzed Bureau of Meteorology Queensland region mean sea level isobaric analyses for (a) 0300; (b) 0600; and (c) 0900 on 12 October 1980. See text for explanation of the dashed lines.

dry line cannot now be distinguished from the discontinuity located just south of the Gulf Coast and running ahead of the main trough line. A strong southerly surge accompanied by a spectacular roll cloud was observed at Burketown at about 0710. It is unlikely that the development of this surge would have been known to forecasters preparing the analyses and subsequent forecasts for the area. By 0900 the surge had moved out over the gulf (Fig. 15c); inland, surface heating had commenced and the main trough line had reestablished north of the cool air boundary, which by this time had become less distinct. However, the trough remained connected to the cold front associated with the slowly moving depression to the south.

Without better data, the difficulty of locating significant weather features and the concomitant analysis problems will remain. However, recognition of the existence of morning glory-type surges, both from the northeast *and from the south,* and an appreciation of the synoptic conditions which favor their occurrence, will add to the interpretation of the data that does exist, and thus benefit the forecast.

## 7. Concluding remarks

The occurrence of southerly surges adds to the complexity of synoptic analysis and forecasting in the data sparse area of northwest Queensland, partly because of the large local pressure gradients associated with surges and partly due to the capacity of surges to trigger deep convection when the atmosphere is sufficiently conditionally unstable.

A somewhat expanded data set than was available to Smith et al. (1982) confirms a main result of this paper that southerly surges have the structure of an undular-type bore propagating on a nocturnal, surface-based stable layer, similar to their northeasterly counterparts.

A synoptic feature conducive to the formation of southerly surges is the existence of a ridge of high pressure across central Australia directing a southerly to southeasterly airstream over western Queensland. In some cases, strong ridging occurs during the 12- to 24-hour period prior to the surge and may be preceded by the movement of a frontal trough across central Queensland; in others, the ridge is quasi-stationary and the front is absent. However, the inland heat trough is always a prominant feature. In many cases, a precursor to a southerly surge at Burketown is a marked increase in the southerly component of low-level wind at Mount Isa during the late evening and early morning, followed, some hours later, by an increase in the easterly component, a feature indicative of a nocturnal low-level jet.

Several possible mechanisms of surge formation have been discussed. These include the motion of a front into the developing low-level stable layer, the interaction between the nocturnal low-level jet and the deeply penetrating sea breeze from the southern Gulf coast, and katabatic drainage from the Barkly Tablelands. There is circumstantial evidence that a few surges are generated by the motion of a front, but this does not appear to be the most usual mechanism. The strong association on many occasions between the Mount Isa wind signature and the occurrence of surges points to the role of the nocturnal jet, but the data are inadequate to determine the relative importance of katabatic drainage. They are inadequate also to determine whether the surge is *produced* as a wave-guide disturbance on the low-level stable layer, ahead of the gravity current (or intrusive flow) presumed to be its cause, or whether it comprises a modified form of the gravity current itself, due to the low-level stable layer ahead of it, as in the laboratory experiments described by Wood and Simpson (1984). In either case, the disturbance structure would be similar. It is hoped that numerical model simulations now in progress will shed further light on these questions and provide guidance for future observational studies.

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## REFERENCES


Christie, D. R., K. J. Muirhead and A. J. Hales, 1978: On solitary waves in the atmosphere. *J. Atmos. Sci.*, **35**, 805–825.

——, and K. J. Muirhead, 1983: Solitary waves: A hazard to aircraft operating at low altitudes. *Aust. Meteor. Mag.*, **31**, 97–109.

——, K. J. Muirhead and R. H. Clarke, 1981: Solitary waves in the lower atmosphere. *Nature*, **193**, 46–49.

Clarke, R. H., 1972: The morning glory: An atmospheric hydraulic jump. *J. Appl. Meteor.*, **11**, 304–311.

——, 1983a: Fair weather nocturnal inland wind surges and atmospheric bores. Part I: Nocturnal wind surges. *Aust. Meteor. Mag.*, **31**, 133–145.

——, 1983b: Fair weather nocturnal inland wind surges and atmospheric bores. Part II: Internal atmospheric bores in northern Australia. *Aust. Meteor. Mag.*, **31**, 147–160.

——, 1984: Colliding sea breezes and the creation of internal atmospheric bore waves: Two-dimensional numerical studies. *Aust. Meteor. Mag.*, **32**, 207–226.

——, R. K. Smith and D. G. Reid, 1981: The morning glory of the Gulf of Carpentaria: An atmospheric undular bore. *Mon. Wea. Rev.*, **109**, 1726–1750.

Garratt, J. R., 1985: The inland boundary layer at low latitudes. Part I: The nocturnal jet. *Bound. Layer Meteor.*, **31**, 307–327.

——, and W. L. Physick, 1985: The inland boundary layer at low latitudes. Part II: sea breeze influences. *Bound. Layer Meteor.*, **31**, 209–231.

Maxworthy, T., 1980: On the formation of nonlinear internal waves from the gravitational collapse of mixed regions in two and three dimensions. *J. Fluid Mech.*, **96**, 47–64.

Neal, A. B., I. J. Butterworth and K. M. Murphy, 1977: The morning glory. *Weather*, **32**, 176–183.

Noonan, J. A., and R. K. Smith, 1985: Linear and weakly nonlinear internal wave theories applied to "morning glory" waves. *Geophys. Astro. Fluid Dyn.*, **33**, 123–143.

Physick, W. L., and R. K. Smith, 1985: Observations and dynamics of sea breezes in northern Australia. *Aust. Meteor. Mag.*, **33**, 51–63.

Simpson, J. E., 1982: Gravity currents in the laboratory, atmosphere, and ocean. *Annual Review of Fluid Mechanics*, **14**, 213–234.

Smith, R. K., and J. Goodfield, 1981: The 1979 morning glory expedition. *Weather*, **36**, 130–136.

——, and B. R. Morton, 1984: An observational study of northeasterly "morning glory" wind surges. *Aust. Meteor. Mag.*, **32**, 155–175.

——, and M. A. Page, 1985: Morning glory wind surges and the Gulf of Carpentaria cloud line of 25 October 1985. *Aust. Meteor. Mag.* **33**, 185–194.

——, N. Crook and G. Roff, 1982: The morning glory: An extraordinary atmospheric undular bore. *Quart. J. Roy. Meteor. Soc.*, **108**, 937–956.

Tepper, M., 1950: A proposed mechanism of squall lines: The pressure jump line. *J. Meteor.*, **7**, 21–29.

Wood, I. R., and J. E. Simpson, 1984: Jumps in layered miscible fluids. *J. Fluid Mech.*, **140**, 329–342.