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A review of research on the dry season mesoscale meteorology of northern Australia

Roger K. Smith[a] [1]and Michael J. Reeder[b c]
[a] *Meteorological Institute, Ludwig Maximillians University of Munich, Munich, Germany*
[b] *School of Earth, Atmosphere and Environment, Monash University, Clayton, Australia*
[c] *ARC Centre of Excellence for Climate System Science, Monash University, Clayton, Australia*

Abstract:

An historical account of research on the structure and dynamics of a range of dry-season meteorological phenomena that occur over the arid interior of Australia is presented. These include: undular bores; sea breezes circulations; continental cold fronts in the tropics and subtropics; dry lines; and heat lows or heat troughs. The research was initiated by an expedition mounted in 1979 to gather data on the “Morning Glory”, a spectacular cloud formation that occurs in the Gulf of Carpentaria region. The Morning Glory was found to have the structure of an undular bore. Studies of the other phenomena were stimulated by attempts to understand the origin of southerly Morning Glories. Some outstanding problems that have emerged from the research are discussed.

KEY WORDS bore wave, cloud line, cold front, dry line, heat low, heat trough, Morning Glory

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1 Introduction

It is more than three and a half decades since the first expedition was mounted to gather data on the “Morning Glory”, the name given to a spectacular cloud formation that occurs in the Gulf of Carpentaria region of northeastern Australia. The clouds are seen early in the morning, most frequently towards the end of the late dry season from early September to about mid-November. An example is shown in Fig. 1. That early research led subsequently to questions concerning the structure and dynamics of a range of other dry-season meteorological phenomena that occur over the arid interior of Australia. These include continental cold fronts in the tropics and subtropics, heat lows or heat troughs, sea breezes, which, unimpeded by the low Coriolis forces in the tropics, can penetrate far inland, and dry lines. In this paper we present an historical account of the research and review the scientific advances that have emerged.

We dedicate the paper to the memory of our dear mentor and friend, the late Bruce Morton, who gave so much support to the early field experiments and participated himself in the 1981 and 1982 experiments. His intense curiosity while making measurements in Karumba in 1981 led him to stay up all night for several nights, manually recording surface pressure from a digital barometer every minute!

Figure 1. A photograph of the Morning Glory looking east towards Burketown.

2 The Morning Glory

The Morning Glory comprises a low roll cloud or frequently a succession of roll clouds, sometimes stretching from horizon to horizon. 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. Occasionally they are preceded over land by a shallow layer of fog that they rapidly disperse. They move rapidly across the sky at speeds of 10-15 m s^{-1}, the most usual direction being from the northeast. Occasionally, cloud lines are observed orientated approximately east-west and moving from the south and, more rarely, ones oriented southwest-northeast

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[1] Correspondence to: Prof. Roger K. Smith, Meteorological Institute, Ludwig Maximillians University of Munich, Theresienstrasse 37, 80333 Munich, Germany. E-mail: roger.smith@lmu.de

and moving from the southeast. We refer to these types as northeasterly Morning Glories, southerly Morning Glories and southeasterly Morning Glories, respectively.

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), have wind speeds comparable to the speed of the cloud. The disturbance brings about also an abrupt rise in surface pressure (sometimes more than 1 mb in a few minutes and often a reversal in surface wind direction. The surface pressure may oscillate following the rise, but the increased mean pressure and change in wind direction frequently persist for at least several hours. A typical surface pressure trace is shown in Fig. 2.

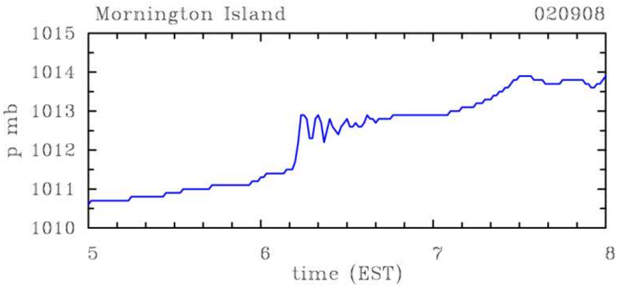


Figure 2. A typical surface pressure trace accompanying the passage of a Morning Glory taken on 2 September 2008 on Mornington Island. There is normally a sharp pressure jump followed by a series of oscillations, which are manifestations of the Morning Glory waves. Note that the mean pressure remains higher than that before the passage of the disturbance (this feature remains true even when one removes the mean diurnal increase that normally occurs at this time of the morning). The abscissa marks Eastern Standard Time (EST) and the ordinate pressure in mb.

2.1 History

Anthropologist Margaret Moore told us that the name of the phenomenon in the language of the Garrawa Aboriginal people who live near the south coast of the Gulf is "kangolgi" and it is credited with increasing the supply of bird life. This may reflect the fact that the Morning Glory occurs most frequently in October, just prior to the "wet" season, which is a harbinger of bounty for the Aboriginal people.

The earliest published description of the Morning Glory of which we are aware is in the Royal Australian Air Force (1942, Part 2, p. 25), where it is described as a "land breeze" coming out of the east about dawn with a squally onset and with one or several long straight lines of low cloud. Thirty years later, Clarke (1972) explored the possibility that the phenomenon could be interpreted as a propagating internal hydraulic jump, formed at a discontinuity in the slope of the ground, on a katabatic flow developing on Cape York Peninsula. Clarke's theory was inevitably tentative, since the only available data against which it could be compared were a series of autographic records of surface pressure, wind and temperature at the (now abandoned) weather station at Karumba. Moreover, the theory did not take account of the strong heating contrasts between sea and land in the Gulf region. In fact, there appeared to be the possibility that local sea breeze circulations might be a more important influence than the katabatic flow.

A few years later, Neal et al. (1977) carried out a study of pressure jumps recorded on weekly Bureau of Meteorology barographs around the gulf at Edward River, Kowanyana, Normanton, Burketown and Mornington Island. These data enable estimates to be made of the speed and orientation of a number of pressure jump "lines", presumably associated with Morning Glories. It was shown that the majority of lines were roughly parallel with the east coast of the Peninsula (and also to the coastal ranges which rise to a height of between 300 and 500 m in the Dividing Range) and move with a speed of typically 10 m s^{-1}.

A climatology of pressure jumps was presented also, showing frequencies of occurrence at the five stations in terms of time of day and month, and mean sea level isobaric charts for pressure jump days and for days free of jumps. The latter were classified according to whether surface winds were southeasterly or northeasterly in the southeast gulf area.

In October 1978, Reg Clarke, a former long-time research scientist with the then CSIRO Division of Atmospheric Physics, and his wife, Elsje, staged a small expedition to the gulf with a view to collecting more detailed surface data on Morning Glories as well as photographs and time-lapse movie film of the clouds. Ten days were spent in the field during which time four Morning Glories were observed, a frequency which, coincidentally, corresponded with the average frequency of presumed Morning Glories at Karumba in October, based on nine years of data (Neal et al. 1977). Two of these four occurred before daybreak; one was cloud-free; two had five parallel cloud bands and the other three. All had marked wind and pressure jumps. One was followed by car over 35 km and its speed measured at 11 m s^{-1}; another was photographed in time-lapse which revealed a rolling motion of the cloud band with upward motion at the leading edge and downward motion at the rear. In each case, measurements of surface pressure, temperature, humidity and wind were made during the passage of the disturbance.

2.2 The first field experiment

Early in 1979, a more ambitious expedition was planned, led by Reg Clarke and the first author, with six other participants (Fig. 3). It had two main objectives. The first was to observe the structure of Morning Glories, both in the horizontal and vertical, as they passed Burketown, with a view to identifying the mechanisms associated with its propagation and maintenance. The second objective was to obtain surface data on Cape York Peninsula in an attempt to identify the region of origin and to determine the formation

Figure 3. Participants of the 1979 Morning Glory expedition. From left to right: standing: Reg. Clarke, Richard Hagger, Jonathan Goodfield, Karen McAndrew, Roger Merridew (pilot), Roger Smith, kneeling: Terry Long, Derek Reid, Peter Watterson, and Elsje Clarke.

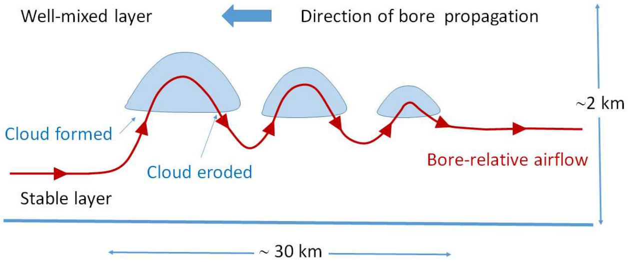


Figure 4. Schematic of the vertical structure of a Morning Glory. The bore is propagating from right to left. The airflow relative to the bore is from left to right. The Morning Glory clouds form as air ascends ahead of each wave and they evaporate as air descends behind each wave. The continuous formation of cloud at the leading edge of the wave gives the appearance that the clouds are rotating and for this reason, the clouds are often referred to as "roll clouds".

mechanism of the phenomenon. To accomplish the first of these tasks, the expedition was equipped with theodolites for making pilot balloon wind measurements and a light aircraft to make airborne measurements of temperature and humidity. The expedition lasted two weeks from late September to early October during which time three Morning Glories occurred at Burketown. An unprecedented amount of data were collected on these events and the subsequent analysis of the data, together with automatic weather station (AWS) data collected on the peninsula was presented in a paper by Clarke et al. (1981). A brief description of the experiment was given by Smith and Goodfield (1981). A disturbance was observed also on the morning when the expedition party was about to leave Burketown, but no data were obtained, except photographs. An intriguing feature of this disturbance was that unlike the others, it was moving from the south!

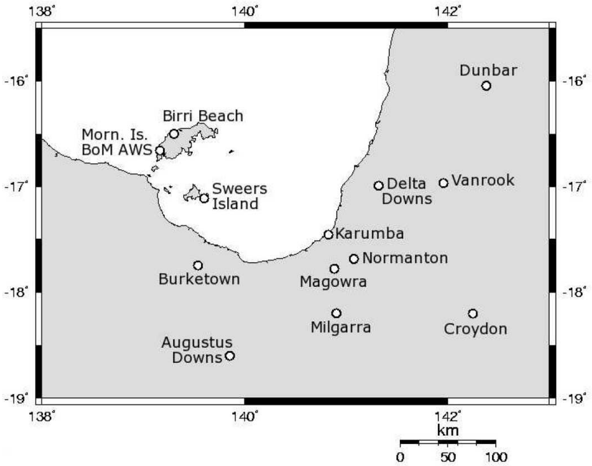
About the same time as the foregoing expedition and unbeknown to its leaders until after the expedition, Christie et al. (1979) reported a study of intrusive-type flows and solitary waves in the lower atmosphere observed in microbarograph records at the Warramunga Seismic Station at Tennant Creek, about 600 km west-southwest of Burketown. Based on the results of their analyses, Christie et al. (p4968) expressed the opinion that: ". . . it seems very likely that the Morning Glory phenomenon is in fact a manifestation of a fairly well-developed large-amplitude isolated solitary wave or group of solitary waves. In this interpretation the roll clouds are associated with the closed circulation cells in the streamline pattern of large-amplitude deep-fluid internal solitary waves propagating along a marine inversion." The data obtained during the 1979 expedition broadly supported this view.

2.3 Structure and origin of the Morning Glory

Analysis of data from the 1979 expedition showed that the Morning Glory had the structure of an undular bore propagating on a stable layer of air in the lowest half to-one kilometre of the atmosphere (Clarke et al. 1981). The structure is analogous to that of undular bores that form on tidal rivers. An undular bore is a weak hydraulic jump which, loses energy through the downstream propagation of internal (possibly solitary) waves instead of dissipating energy through turbulence as in strong hydraulic jumps. The clouds are essentially wave-type clouds associated with the constituent bore waves (see Fig. 4). As a wave crest approaches, air parcels rise and cool and condensation occurs leading to cloud. Then, as the wave crest passes, the air parcels descend and warm so that the cloud re-evaporates. Thus the clouds are not simply being carried along with the air flow: rather cloud is continuously being formed at the leading edge of each wave and continuously eroded at the trailing edge.

Wave propagation, itself, requires a wave guide. The data from the 1979 expedition showed that the wave guide for the Morning Glory is related to the particular thermal structure of the lower atmosphere in the southern region of the gulf, which exhibits of a deep well mixed (neutrally-stable) layer overlying a shallow stable layer. The neutral layer aloft is a result of the deep well-mixed layer formed over the land on the previous day and the stable layer is associated with cooler air that exists over the sea. Further aspects of the Morning Glory waveguide including the effects of the vertical wind profile are discussed in subsection 8.

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 waves remain. For this reason, 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 inland from the coastal region. Some authors (e.g. Clarke 1983a,b, Smith and Morton 1984) have used the term "wind surge" to describe the overall disturbance. It may be noted that because of strong (dry) convective overturning, the low-level stable layer over the land rarely survives into mid-morning. However, there is evidence from surface micro-barograph data that disturbances continue to propagate in some form for a considerable distance inland during the day (Christie et al. 1978). The nature of the wave guide at this stage of the disturbance remains to be determined.



(b)

Figure 5. Maps of the southeast portion of the Gulf of Carpentaria region showing the location of some of the stations from which data have been collected.

Analyses of AWS data (Clarke et al. 1981, Clarke, 1983b) supported by numerical model simulations (see section 2.6) indicate that northeasterly Morning Glories 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. However, the collision, itself, has not been observed: the only information we have about the details of it has emerged from high resolution numerical model simulations and a few laboratory experiments (see subsection 7). In fact, this aspect of the problem is perhaps the least well understood.

The origin of Morning Glories from the south is now reasonably well understood (section 3) and it seems that most, if not all, are generated by shallow cold fronts (section 9). It is known that southerly Morning Glories have the same bore-like structure of their northeasterly counterparts (Smith et al. 1982). Perhaps remarkably, with a few exceptions, they tend to occur at Burketown (see Fig. 5 for locations) at much the same time as northeasterly ones, typically between about 0500 and 0800 EST. (EST refers to eastern standard time = GMT+ 10 hours.)

Several more field experiments were organized in the decade following the 1979 expedition and many more disturbances were documented, including a few from the south (Smith et al. 1982, Smith and Morton 1984, Smith and Page 1986, Smith et al. 1986). Some more recent field experiments are described in subsection 3.

2.4 Favourable synoptic conditions

The occurrence of northeasterly Morning Glories appears to be favoured by a synoptic-scale ridge of high pressure along the east coast of Queensland with associated north-easterly geostrophic winds over Cape York Peninsula. An example is illustrated by the mean sea level pressure analyses at 1000 EST on 24 September 2006 shown in Fig. 6. A Morning Glory was observed over the southern gulf early on the following morning.

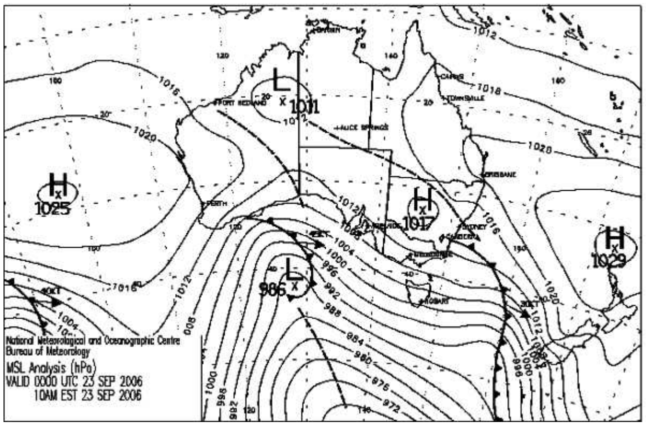


Figure 6. Bureau of Meteorology mean sea level pressure analysis at 1000 EST on 24 September 2006 showing synoptic conditions conducive to the formation of northeasterly Morning Glories. A prominent feature is the ridge along the east coast of the Australian continent that directs a northeasterly component of flow across Cape York Peninsula.

2.5 Climatology

Nudelman et al. (2010) presented a climatology of nocturnal or late morning pressure jumps at stations around the Gulf of Carpentaria and at one inland station south of the Top End. The climatology was based on one-minute average data from Bureau of Meteorology's AWSs. Of the 21 bore-like disturbances that were recorded at three or more stations during the four-month period August-November 2006, 16 were from the northeast sector and five had a significant southerly component. One of the latter was recorded as far west as Daly Waters. Only one northeasterly disturbance was identified at Groote Eylandt in the north-west of the Gulf.

Their study highlights the value of one-minute data in identifying the passage of all types of low-level disturbances at surface stations. Such passages would be missed with the conventional hourly or even three-hourly data routinely available to forecasters. It was found that a pressure jump criterion of about 0.25 mb in three minutes is suitable for detecting the majority of morning-glory-type disturbances. Since their study was initiated, considerably more data have become available and provide a rich source of material to extend this climatology in the future.

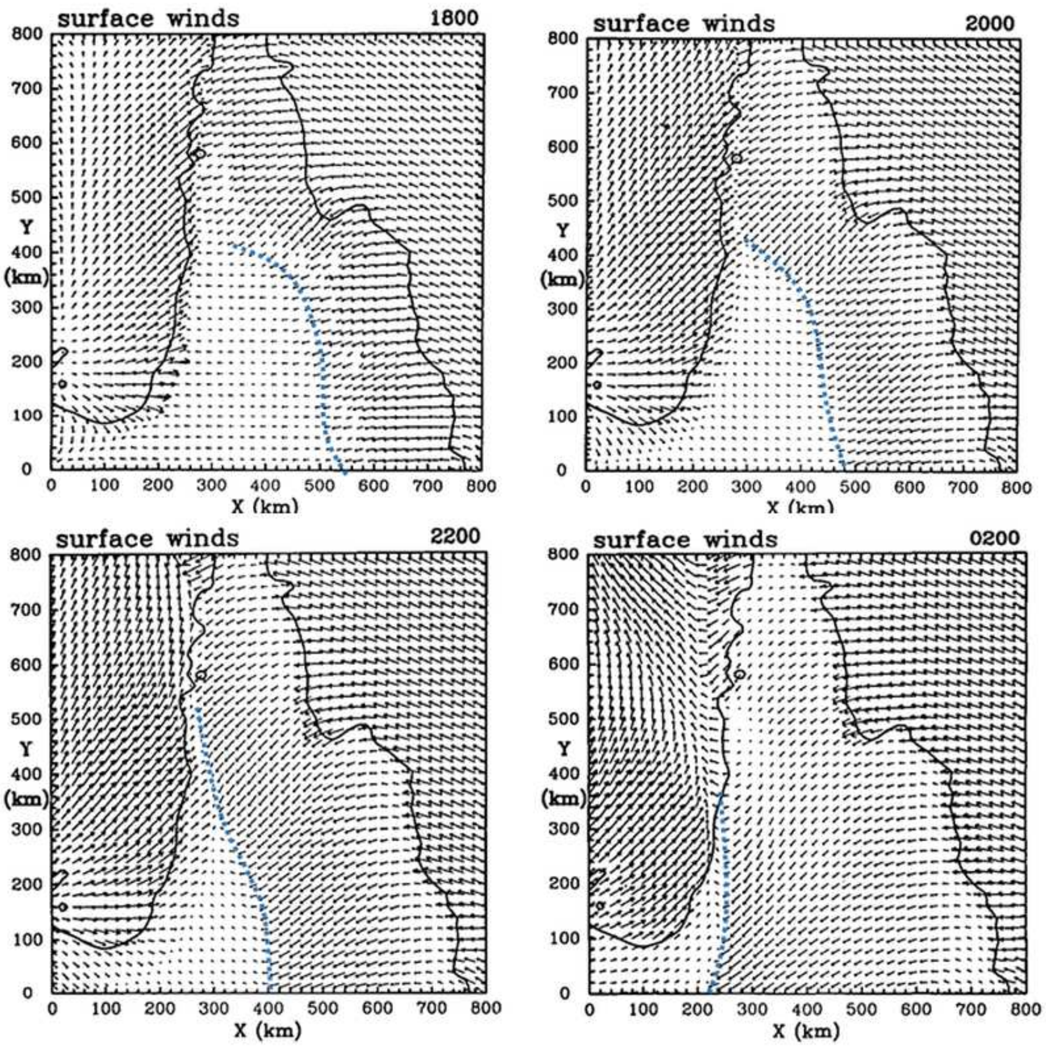


Figure 7. Results of a numerical model simulation of sea breezes over Cape York Peninsula illustrating the formation of the east-coast sea-breeze front (the blue dashed curve) and its progressive collision with the west-coast sea breeze on the western side of the peninsula during the evening. From Smith and Noonan (1987).

2.6 Numerical simulations

The data obtained from the various field experiments motivated attempts to simulate the Morning Glory using numerical models, or at least the sea-breeze circulations that were believed to lead to it. Two first attempts were those of Clarke (1984) and Noonan and Smith (1986), both using two-dimensional models for the flow in a vertical cross-section across Cape York peninsula. Shortly after, Noonan and Smith (1987) carried out a three-dimensional simulation over a domain that included the peninsula. The results supported the presumed role of sea-breeze circulations over Cape York Peninsula in the generation of the Morning Glory. The collision of the east- and west-coast sea breezes under conditions of a moderate (5 m s^{-1}) easterly synoptic flow is manifest as a convergence line that extends progressively southwards with time along the entire length of the Peninsula near the west coast (see Fig. 7). Collision of the sea breezes occurs in the late afternoon or early evening in the north of the peninsula, where the peninsula is comparatively narrow and progressively later in the south, where the peninsula is much broader.

The rapid development of computer power in the 90's provided the possibility of repeating the foregoing calculations with higher spatial resolution and a over a larger domain. A set of such calculations was reported by Smith and Noonan (1998). While these calculations examined a range of additional features of the precursors to Morning Glories, they confirmed also the results of earlier ones concerning the role of sea breezes. For example, calculations for a range of horizontally-uniform geostrophic flows over the region, with directions typical of those that occur during the dry season, showed that the development of westward-moving lines of low-level convergence over the gulf is the rule. This explains why travelling convective- and wave-cloud lines are commonly observed there. The convergence lines are associated with the leading edge of sea-breeze circulations that develop over Cape York Peninsula and around the gulf.

For easterly and northeasterly geostrophic flows, the circulations that develop are broadly repeatable from day to day, despite the relatively long inertial period (nearly two days) in the region. However, this is not the case for a southeasterly flow. Calculations with and without orography showed that the orography on Cape York Peninsula enhances the low-level easterly flow over the eastern side of the peninsula, but delays the formation of the Morning Glory convergence line on the western side. Although it affects the detail, orography does not play a fundamental role in the generation of the Morning Glory.

Goler and Reeder (2004) used a high-resolution cloud model to explore in detail the generation of the Morning Glory. The model was two-dimensional and nonhydrostatic and simulated an east-west cross section of the southern part of Cape York Peninsula with a horizontal grid spacing of 200 m. The calculations were initialized at sunrise with a 5 m s^{-1} easterly flow and a temperature and humidity sounding taken upstream from the peninsula. Figure 8a shows the wind and potential temperature fields from the model at 2210 LST, which is close to the time at which the sea breezes meet. For clarity, only a small part of the model domain focussed on the point of collision is shown. As in earlier studies, the sea breezes that develop over the peninsula are highly asymmetric with the east-coast sea breeze being both deeper and warmer than its western counterpart. The asymmetry is due to the ambient easterly flow over the peninsula.

The east-coast sea breeze is warmed as it propagates across the heated land and when the sea breezes meet, it rides over the west coast sea breeze (as in the laboratory experiments of an intrusive gravity current described in section 7). In the process it produces a series of waves that propagate on the on the pool of cold air laid down by the west coast sea breeze. The calculations showed that when the phase speed of these waves matches the westward propagation speed of the east-coast sea breeze, the waves grow to large amplitude, thereby forming the Morning Glory. When the east-coast sea breeze propagates too fast relative to the waves, the waves do not amplify.

Goler and Reeder concluded that the Morning Glory is generated by a resonant coupling between the east-coast sea breeze and the disturbances that propagate on the shallow stable layer produced by the west-coast sea breeze. The leading Morning Glory wave generated by the model is shown in Fig. 8b. The number of waves produced is found to depend on the vertical stability of the west-coast sea breeze and the strength of the east-coast sea breeze. As in the calculation by Smith and Noonan (1998), the inclusion of orography representative of Cape York Peninsula does not change the overall result with a Morning Glory forming in much the same way as in the case without orography. The main difference is that the sea breezes meet earlier when orography is included.

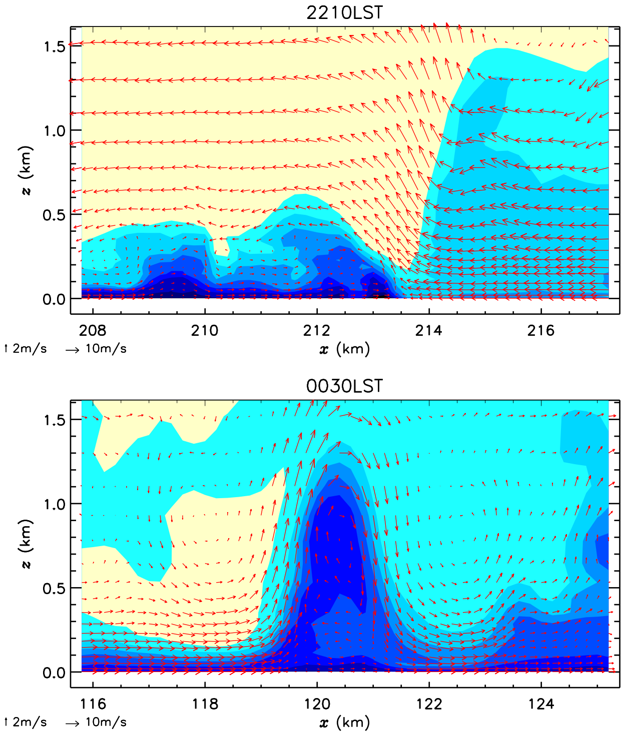


Figure 8. (a) East and west coast sea breezes at 2210 LST. Wind vectors and potential temperature shaded in 1 K increments. (b) The Morning Glory at 030 LST. Wind vectors and potential temperature shaded in 1 K increments. For clarity, only a small part of the model domain is shown. Adapted from Goler and Reeder (2004).

3 Southerly Morning Glories

The observation at Burketown of a Morning Glory moving from the south at the end of the 1979 field experiment was a total surprise, but the existence of such disturbances was reported in the same year based on data from arrays of microbarometers deployed in the region by Doug. Christie and colleagues from the Australian National University (Christie et al. 1979). A year later, two more disturbances were observed during a field campaign and it became apparent that such occurrences were not so uncommon (Smith et al. 1986). A feature of the synoptic mean sea level pressure patterns conducive to the formation of southerly disturbances over northern Australia was found to be the extension of a ridge of high pressure across the continent directing a southerly to southeasterly airstream over western Queensland. In some cases, strong ridging occurs during the 12- to 24-h period prior to the disturbance and is preceded by the movement of a frontal trough across central Queensland; in other cases, the ridge is quasi stationary and the front (at least as commonly analyzed) is absent. However, the inland heat trough is always a prominent feature along the leading edge of the ridge (see section 10). It is well marked in model forecasts as a narrow line of enhanced low-level cyclonic vorticity and, from available observations, it appears to be coincident with the dry line (see section 11). Figure 9 below shows the mean sea level pressure analyses leading up to two well-documented southerly Morning Glory events.

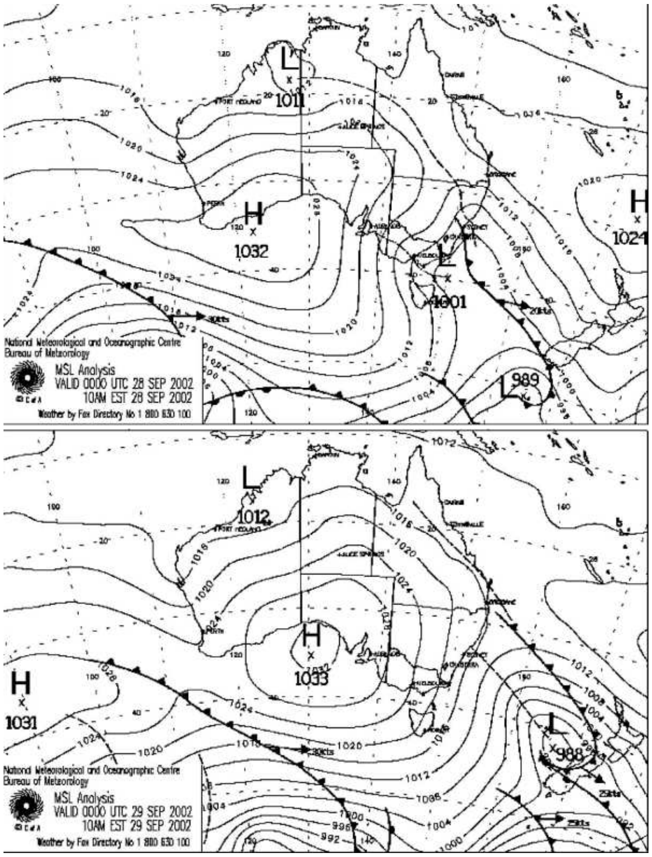


Figure 9. Bureau of Meteorology mean sea level pressure analyses at 1000 EST on 28 September and 1000 EST on 29 September 2002 indicating conditions conducive to the formation of southerly Morning Glories. The southerly Morning Glory was associated with the trough line (marked by a dashed curve) as the line crossed over the southern gulf.

The analyses of available data for the events described by Smith et al. (1986) pointed to a possible connection with cold fronts crossing the continent to the south and also with the inland heat trough. However, at the time, little was known about the structure of fronts that penetrated far northwards across the dry continent. Solving this mystery called for an observational programme to acquire the necessary data. To this end, a pilot experiment was organized September 1988 to document one or two cases (Smith and Ridley 1990) and two subsequent experiments, more extensive in scope, were carried out in early and mid-90’s (see section 9 for further information on these experiments and the accompanying research on subtropical continental cold fronts). During the first of these experiments in 1991, an unprecedented data set was obtained on a cold front that crossed the northern part of the continent and transformed over night into a southerly Morning Glory (Smith et al. 1995).

The foregoing analyses stimulated also a program of research to examine the dynamics of heat lows and heat troughs, the findings of which are summarized in section 10. Two particularly interesting southerly Morning Glories were documented during the 2002 Gulf Line Experiment (GLEX, Goler et al. 2006; see also section 4) and we discuss these briefly in the next two subsections.

3.1 Event of 29 September 2002

One of the southerly Morning Glories reported by Smith et al. (2006) is discussed now. A special feature of this event was the clear double change structure at all automatic weather stations (AWSs) in the southeastern gulf region with an undular bore-like wave preceding and separating from an air mass change in the form of a dry line. As in other major events previously documented, the disturbance was accompanied by ridging over the northeastern part of the continent (Fig. 9). In this case, the ridging was strong enough to push the trough a considerable distance northwards over the gulf and the peninsula. As a result, there was a significant air mass change across much of the AWS network with dry continental air extending well out over the gulf. At Karumba, there were strong southeasterly winds with blowing dust following the change.

Figure 10 shows time series of various quantities from two of the AWS stations: Augustus Downs (one of the southernmost stations) and Birri Beach on the northern side of Mornington Island in the gulf. At the southernmost station, Augustus Downs, the bore wave is evident as a sharp pressure jump at about 2115 EST, accompanied by a sharp increase in wind speed and an abrupt change in wind direction from one slightly west of north to a southerly. A second wave of the bore with a further jump in pressure occurred about 15 min later. The passage of the trough line (effectively a dry line) was marked by a sharp fall in the dewpoint at around 2300 EST, accompanied by a slight increase in temperature and a rapid freshening of the wind from the southeast. The surface data from Birri Beach show a similar structure, with the bore wave onset at about 0150 EST and the air mass change just after 0645 EST. Thus, the bore wave had separated farther from the air mass change as the disturbance moved northwards.

There was not much of a temperature change recorded at the surface with the passage of the bore wave, although numerical model-based mesoscale analyses of the event do indicate a relatively deep layer of cooler air following the change. The analyses are not necessarily inconsistent with the surface observations, which often show a rise in surface temperature accompanying the passage of a *cold* front over central Australia. The jump in surface temperature is a consequence of the nocturnal formation of a shallow layer of cool air adjacent to the surface, which is destroyed by the downward turbulent mixing of warmer air from aloft at the front.

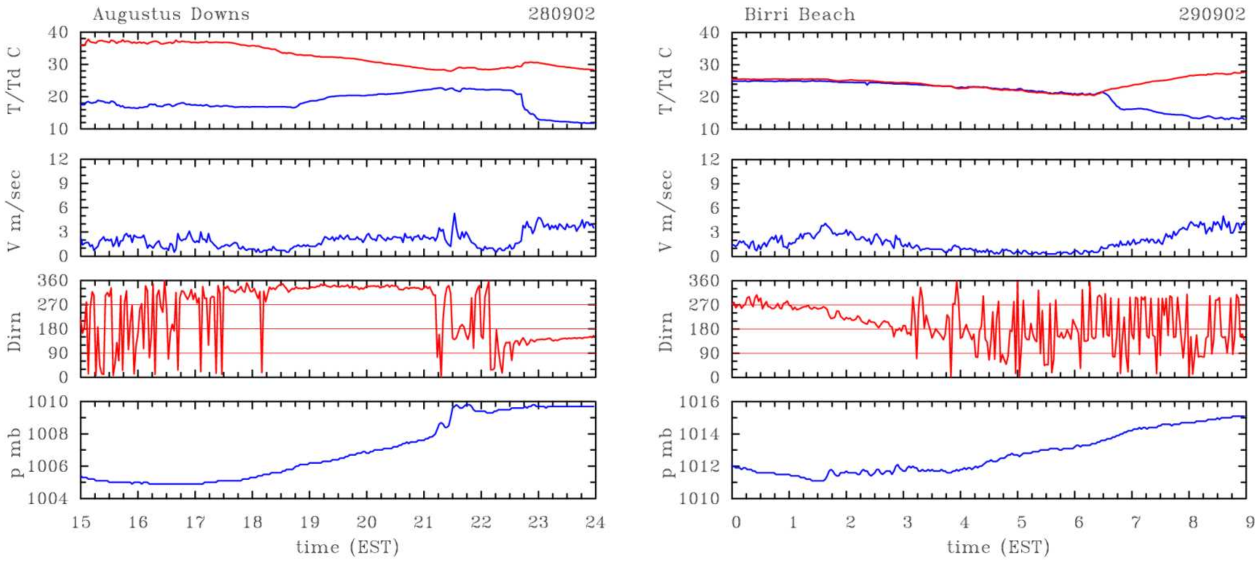


Figure 10. Time series of temperature, dewpoint temperature (dashed), wind speed and direction, and pressure from two AWS stations at (left) Augustus Downs and (right) Birri Beach on Mornington Island during the passage of the southerly disturbance of 28-29 September 2002. Adapted from Smith et al. (2006).

3.2 Event of 9 October 2002

A second event from Smith et al. (2006) is discussed in this subsection. On this day, three Morning Glories were observed, one moving from the southeast, one from the south and the other from the northeast. These disturbances were documented in unprecedented detail with airborne measurements as well as surface observations. (Only once previously, on 10 October 1990, had Morning Glories been observed simultaneously propagating from all three preferred directions; see Christie 1992, and Reeder and Christie 1998.) The synoptic situation was very similar to that for the previous disturbance, namely a ridge of high pressure moving across the continent and the inland trough line on its northeastern side moving northeastwards towards the gulf (see Fig. 11). Recognition of this favourable pattern, which emerged from the earlier studies of Smith et al. (1982, 1986), enabled us to forecast the event 8 days ahead on the basis of the Bureau of Meteorology's global numerical prediction system. With this amount of lead time it was possible to deploy the instrumented research aircraft available to the experiment. Note that a feature of the synoptic situation favourable for the southerly Morning Glories shown in Figs. 9 and 11) is the ridge along the east coast of Australia, which is favourable also for the generation of northeasterly Morning Glories as well (see Fig. 6).

Sometime overnight on 8 October, southerly, southeasterly, and northeasterly Morning Glories developed. The most prominent feature in the Geostationary Meteorological Satellite (GMS) visible image at 0832 EST 9 October is the series of cloud lines in the southeastern corner of the gulf (Fig. 12). The family of cloud lines oriented northeast-southwest is the southeasterly Morning Glory. There is a cloud line oriented northwest-southeast also, marking the northeasterly Morning Glory, and a group of cloud lines essentially oriented east-west marking the southerly Morning Glory. The wave crests of each family are noticeably curved in the region in which they intersect. A line of moderately shallow convective cloud, a so called North Australian Cloud Line (NACL), is visible also in the northeastern part of the gulf. The NACL will be discussed in section 4.

The AWS trace at Augustus Downs (Fig. 13) shows the passage of a single southerly disturbance at 0400 EST marked by a sharp rise in the pressure, a slight decrease in the temperature and dewpoint temperature, and an increase in the wind speed. Ahead of the disturbance the wind was southwesterly, but as the disturbance approached, the wind backed to become southerly. Our data are inadequate to determine whether this disturbance was the southerly or southeasterly disturbance. The trace shows also the passage of the trough and dry line, which arrive at 0715 EST and are marked by a pronounced decrease in dewpoint temperature, an increase in wind speed, and the onset of a strong south-southeasterly flow.

Based on the foregoing analyses as well as simulations of the events using a mesoscale numerical model (Weinzierl et al. 2007), enabled us to construct a conceptual model of a possible mechanism for the formation of southerly Morning Glories south of the gulf. This model is shown in Fig. 14 Frontogenesis occurs to the south of the heat trough after sunset. The strengthening cold front moves equatorward and collides with the sea breeze to the north of the trough. The sea-breeze air provides a surface-based stable layer and a deep layer of well-mixed air from the continent lies over the sea breeze. Together these form a wave guide on which the bore waves can propagate towards the north.

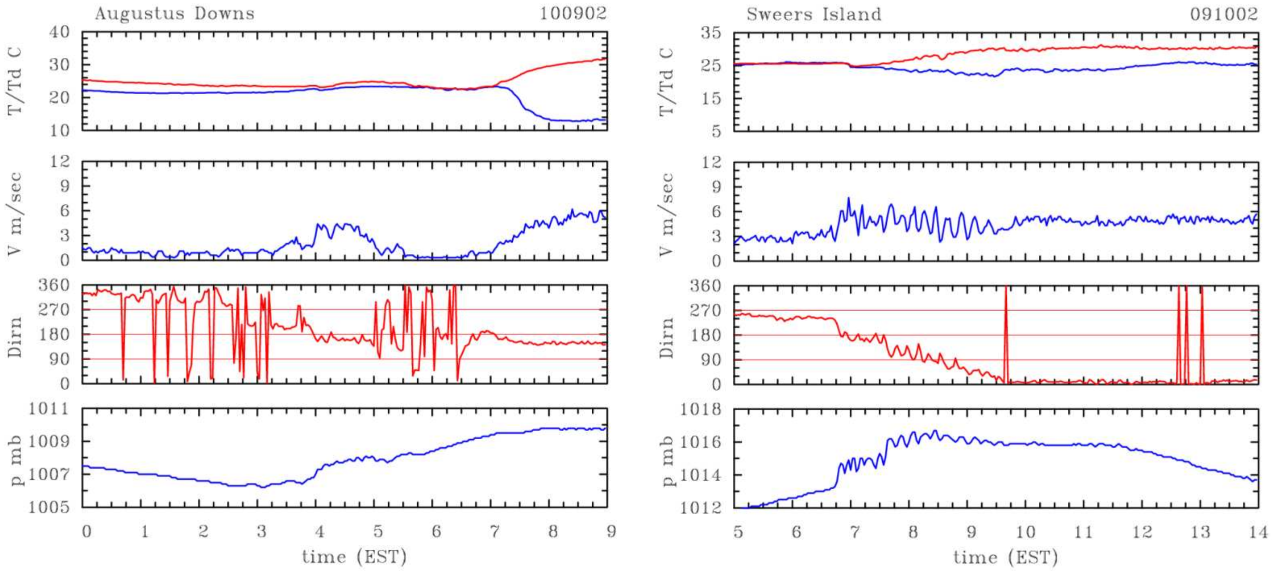


Figure 13. Time series of surface data at (left) Augustus Downs and (right) Sweers Island on 9 October 2002. Temperature (T, solid curve in top panels) and dewpoint temperature (Td, dashed curve in top panels), wind speed (V), direction (Dirn), and pressure (p). The southerly Morning Glory arrived at Sweers Island at 0645 EST and the southeasterly arrived at 0740 EST. Adapted from Smith et al. (2006).

4 The North Australian Cloud Line

The Gulf of Carpentaria region is frequented not only by Morning Glory wave clouds, but also by a range of convective cloud lines, often referred to generically as North Australian Cloud Lines (NACLs) or simply gulf lines. Such lines form in the early evening along the northern part of the west coast of Cape York Peninsula, where the peninsula is relatively narrow. Subsequently, they move westwards across the gulf during the night and following day. Like the Morning Glory, they originate as a result of the collision between the two sea breezes from the east and west coasts of the peninsula, which for a typical broadscale easterly flow occurs near the west coast of the peninsula in the late afternoon (see e.g. Goler et al. 2006, Reeder et al. 2013). During the dry season the cloud lines are mostly composed of shallow cumulus or cumulus congestus clouds, whose vertical development is hindered by the trade wind inversion at about 3 km. However, during the moist season the cloud lines may develop as lines of thunderstorms that pose a significant forecasting problem in the region (Drosdowsky and Holland, 1987, Drosdowsky et al. 1989, Goler et al. 2006). An example of a dry-season case is shown in Fig. 15.

In September 2002, a major field experiment (the Gulf Lines EXperiment, GLEX) was organized by the Bureau of Meteorology, Monash University and the University of Munich to study the NACL (Goler et al. 2006). Following GLEX, two further experiments were organized to study cloud lines over the Gulf of Carpentaria region: GLEX II in 2005 and GLEX III in 2006. GLEX II was carried out in December to investigate the initiation of the NACL, which was accomplished using a small autonomous aircraft and two Doppler sodars. GLEX III focused on Morning Glories over the southern part of the gulf region. This experiment involved Doppler sodar measurements as well as high-temporal-resolution data from operational AWSs. The findings from GLEX II and III were reported by Reeder et al. (2013).

4.1 Summary of observations

The observations at Weipa showed that the degree of asymmetry between west-coast and east-coast sea breezes (as characterized by the wind field alone) depends on the strength of the background easterlies. No NACL developed on any day for which the maximum easterly measured by the sodar was less than 5 m s^{-1}, whereas an NACL formed on every day on which the maximum easterly exceeded 5 m s^{-1}. At Normanton, the sodar winds showed that amplitude-ordered solitary waves developed downstream when the background easterlies were less than about 10 m s^{-1}. In contrast, either no jump or a single bore-like jump formed downstream when the background easterlies were greater than 10 m s^{-1} below a height of 700 m (which is the depth of the boundary layer covered by the sodars). Taken together, the observations from the two field experiments, carried out at opposite ends of the Cape York Peninsula, suggested that strong easterlies favour the formation of the NACL in the northwestern part of the peninsula, whereas weak easterlies favour the formation of the Morning Glory in the southwest. This point is expanded upon in section 8.

4.2 Numerical simulations

Thomsen and Smith (2006) described high-resolution numerical model simulations of low-level convergence lines that were documented during the GLEX experiment.

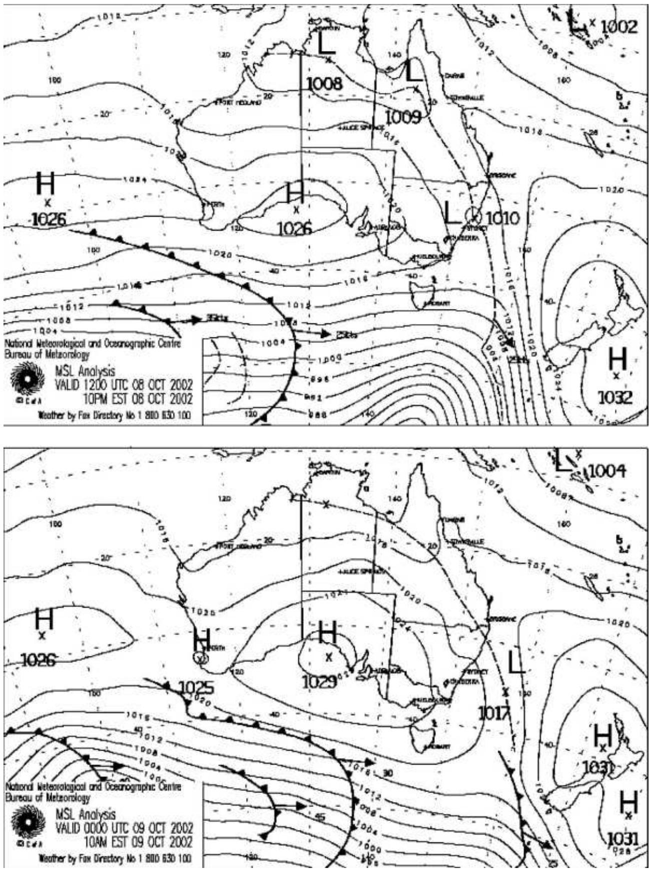


Figure 11. Bureau of Meteorology mean sea level pressure analyses at 2200 EST on 8 October and 1000 EST on 9 October 2002, again indicating conditions conducive to the formation of southerly Morning Glories. The southerly Morning Glory was associated with the trough line (marked by a dashed curve) as the line crossed over the southern gulf.

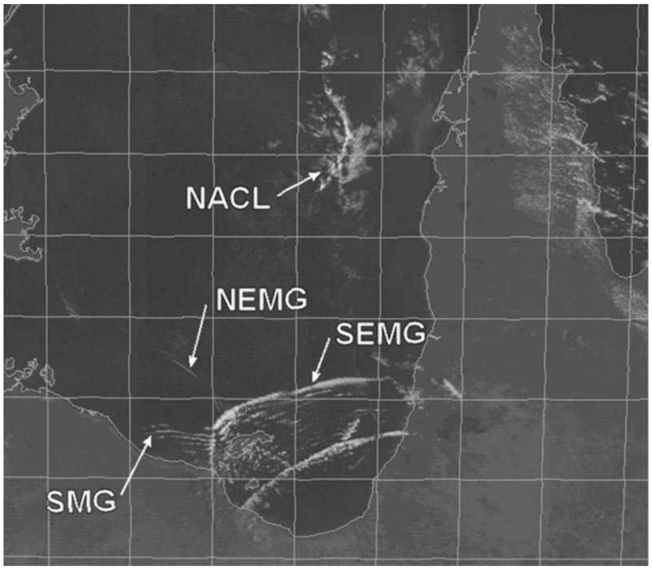


Figure 12. GMS satellite image of the gulf region at 0832 EST on 9 October (2232 UTC 8 October). The four sets of cloud lines identified are the north Australian cloud line (NACL), the southerly Morning Glory (SMG), a southeasterly Morning Glory (SEMG), and a northeasterly Morning Glory (NEMG). From Smith et al. (2006).

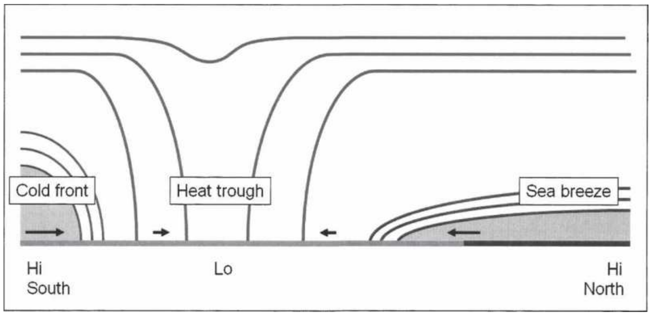


Figure 14. Conceptual model for the inland trough and its tendency to spawn southerly Morning Glory bore waves at night. A meridional cross section of the isentropes (solid lines) is shown with the coldest potential temperatures shaded and the component of low-level airflow indicated by arrows. (From Weinzierl et al. 2007).

The calculations provided further insights into the dynamics of the convergence lines and the mechanisms involved in their formation. Notably, they show two clearly distinct convergence lines, one that corresponds to the Morning Glory and the one that corresponds to the NACL. The former originates from the east-coast sea breeze over Cape York Peninsula south of about 14^{o}S, while the latter originates from the east-coast sea breeze north of this latitude. The calculations support also the conceptual model for the generation of southerly Morning Glories shown in Fig. 14. In particular, they show the separation of a bore-like disturbance following the collision of a nocturnal cold front to the south of the inland trough with a sea-breeze front to the north of the trough. Moreover, they show the progressive transition of the east-coast sea-breeze front and the inland cold front from gravity-current-like flows to bore-like disturbances overnight to form north-easterly and southerly Morning Glories, respectively.

Numerical simulations reported in Reeder et al. (2013) show that the structure of convergence line produced depends on the strength of the collision between the sea breezes from each side of the Cape York Peninsula, which in turn depends on the strength of the background easterlies. When the easterlies are weak (< 10 m s^{-1}), the sea breezes have similar depths and strengths, and their collision leads to a relatively violent disturbance, whereas when the background easterlies are strong (> 10 m s^{-1}) the sea breezes have very different depths and strengths and the disturbance resulting from their collision is comparatively benign.

The foregoing results are consistent with the observational and numerical modelling work from GLEX I. Goler *et al.* (2006) found that the NACL develops at the leading edge of a weak gravity current, referred to as a land breeze by these authors, which moves westwards from Cape York

Figure 15. Aerial view of a North Australian Cloud Line over the Gulf of Carpentaria.

Peninsula as the west-coast sea breeze decays. Strong easterly flow was found behind the NACL with much weaker easterlies ahead of it. In numerical simulations, Goler *et al.* found that this land breeze was accompanied by convergence and upward motion at the leading edge of the weak low-level cold pool, leading to the development of cloud. Presumably, NACLs require relatively strong background easterlies because such a flow produces stronger low-level cold advection and, hence, stronger temperature gradients at the leading edge of the land breeze. The numerical simulations reported in Reeder et al. (2013) is consistent also with the calculations of Goler and Reeder (2004), who found that Morning Glories did not develop when the background easterly flow exceeded 10 m s^{-1}.

Calculations by Thomsen and Smith (2008) showed the importance of the boundary layer parameterization in the numerical prediction of low-level convergence lines during the GLEX experiment. Calculations using five different parameterizations were compared with the observations to determine the optimum scheme for capturing these lines. The schemes that give the best agreement with the observations are the three that include a representation of counter-gradient fluxes and a surface layer scheme based on Monin-Obukhov theory. One of these, the Medium-Range Forecast scheme, is slightly better than the other two, based on its ability to predict the surface pressure distribution. The findings are important for the design of mesoscale forecasting systems for the arid regions of Australia and elsewhere.

5 Forecasting possibilities

Following a preliminary study by Jackson et al. (2002), Weinzierl et al. (2007) examined the possibility of predicting low-level convergence lines over northeastern Australia such as those which give rise to the Morning Glory. They used a mesoscale version of the Australian Bureau of Meteorology's operational Limited Area Prediction System (MesoLAPS) and examined also aspects of the dynamics of such cloud line disturbances. The predictions were made during the GLEX Experiment and were compared with data collected during the experiment. An analysis of the entire 44-day period between 11 September and 24 October showed that with appropriate interpretation, MesoLAPS had significant skill in forecasting the lines, but it did not capture all of them. About 85% of forecasts of northeasterly Morning Glories and southerly Morning Glories, or of their nonoccurrence, were correct, while the corresponding percentage for the NACL was about 65%. However, about 15% of northeasterly Morning Glories and about 35% of NACL events that occurred were not forecast by the model. Only 6 out of 11 southerly Morning Glories were forecast.

The predicted orientation of the Morning Glories was acceptable with a standard deviation error of 6^o. In about 50% of the cases, the times of passage were within an hour of those observed and there was a marked tendency for the predicted lines to be late. MesoLAPS usually shows light winds at low levels ahead of the convergence lines with a sharp increase in wind speed behind the lines as is observed.

In the case of the two southerly Morning Glories discussed in subsections 3.1 and 3.2, the model was able to capture the separation of a bore-like disturbance from the air mass change, although the model does not have the resolution to capture the wave-like structures that develop at the leading edge of the bore waves. A detailed analysis of the MesoLAPS calculations indicated that the broad-scale generation mechanisms of northeasterly and southerly Morning Glories are similar and it enabled the construction of a conceptual model for the generation of southerly Morning Glories shown in Fig. 14.

6 Morning Glories in other parts of Australia

Although most research has focused on Morning Glories in north-eastern Australia, and especially on north-easterly disturbances, similar disturbances have been reported elsewhere in Australia; e.g. the Australian National University Warramunga Research Station near Tennant Creek (Christie et al. 1978, 1979, 1981); central Australian dry salt lakes (Physick and Tapper 1990); Sydney Airport (Manasseh and Middleton 1995); and central New South Wales (Drake 1985). Those reported over southern Australia appear to have been associated with cold fronts as they propagate into stable marine layers or thunderstorm outflows; e.g. the Spencer Gulf South Australia (Robin 1978, Drake 1984); various locations over southern Australia (Clarke 1986); the Great Australian Bight (Schmidt and Goler 2010); Melbourne's Port Phillip Bay (Physick 1986); in advance of the Black Saturday cold front (Engel et al. 2013).

Another region of Australia where Morning Glory-like cloud lines are observed regularly is off northwest Australia over the Indian Ocean. The first documentation of cloud lines in the region are due to Neal and Butterworth

(1973) and Smith (1986). Using visible satellite imagery, Birch and Reeder (2013) produced a climatology of wave-clouds in the region and found that two main types of cloud lines form over northwestern Australia. The first type occur (at least) 2-3 times per month throughout the entire year and are very similar in appearance to the Morning Glory of northeast Australia. Using the Met Office Unified Model, Birch and Reeder simulated the generation of an example of this first type of wave cloud. The Morning Glory-like waves developed in synoptic-scale, low-level southeasterly flow with a heat low along the northwest coast of Australia. At night, the offshore southeasterlies accelerate into the heat low and collide with the onshore sea breeze. The southeasterlies override the sea breeze, much like an intrusive gravity current, and the wave-cloud lines form at the leading edge of this front. (See section 7.)

The second type of could lines are convectively-generated; they are more circular in shape and appear to originate from convective storms and occur (at least) once per month during the wet season. The wave-cloud discussed by Smith (1986) appears to have been of this second type. He reported that the cloud lines appeared to have been generated by the interaction between the onshore sea breeze and a northward-propagating gust front produced by the convective storms north of Port Hedland during the afternoon. Radiosonde observations from Port Hedland that morning showed a surface-based stable layer, formed by the previous day's sea breeze and nocturnal radiative cooling. Above this lay a near-neutral layer, produced by strong diurnal heating on the previous day. This configuration presumably provided an effective waveguide for the propagation of disturbances produced by the collision of the two flows. (See section 8.) Using the Met Office Unified Model, Birch and Reeder found that that vertical wavelength was the depth of the troposphere. Such convectively generated wave modes can produce lifting in the low part of the troposphere, thereby increasing the Convective Available Potential Energy (e.g. see Lane and Reeder 2001).

7 Laboratory experiments with colliding gravity currents

The collision of two sea breezes can be illustrated in a relatively simple laboratory experiment. The apparatus consists of a 2.5 m long plexiglass tank filled with water (Fig. 16). At each end of the tank are regions which can be isolated by two vertical plates. Salt and coloured dye are added in these regions to increase the density of the water by different amounts. The water on the left (coloured blue) has more salt added per unit volume than the water on the right (coloured red) and is therefore heavier than the red coloured water.

At the start of the experiment, both retaining plates are removed and the heavier water on the left and right flows towards the lighter uncoloured water as a pair of gravity currents. The blue-coloured water flows to the right (Fig. 17a) and the red coloured water to the left (Fig. 17b). Ultimately the two gravity currents collide and the lighter of the two, coloured red, ascends above the heavier blue coloured current (Fig. 17c). Following the collision, a wave is generated on the heavier (blue) water and this wave runs to the left, ahead of the red water. It is followed by an "intrusion" of the red water as a sort of tongue between the blue and uncoloured water. The point at which the two gravity currents collide is chaotic and very turbulent. One may think of the blue coloured water as the west-coast sea breeze over Cape York Peninsula, the red coloured water as the warmer east coast sea breeze, and the wave moving to the left on the blue water as the Morning Glory.

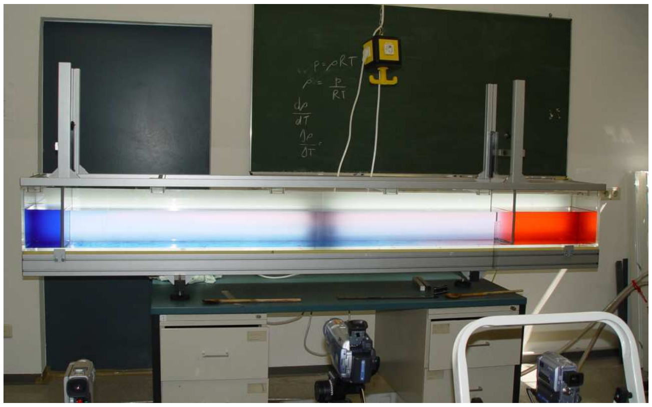


Figure 16. A simple laboratory experiment to demonstrate the interaction of two sea breezes of different densities. See text for a description of the experiment.

8 Theoretical aspects

Weakly nonlinear wave theory is the foundation of much of the early theoretical description of the Morning Glory. For an erudite review see Christie (1992). Before discussing its application to the Morning Glory, a brief summary of the main points of the weakly nonlinear wave theory is useful. There are two versions of this theory. The first deals with long waves on a single, homogenous fluid layer and may be applicable to waves spanning the depth of the troposphere. In this version the governing equation is the Korteweg-de Vries (KdV) equation. The second version of the theory deals with long internal gravity waves propagating on a shallow stable fluid layer with a deep layer of neutrally-stable fluid above. In this version the governing equation is the Benjamin-Davis-Ono (BDO) equation (Benjamin 1967, Davis and Acrivos 1967, Ono 1975). Both the KdV and BDO equations admit steady, propagating solutions, which include solitary and cnoidal (periodic) waves. A general initial disturbance will evolve into a discrete set of amplitude ordered, steadily propagating solitary waves, along with an independent dispersive wave train. The solitary waves are ordered by amplitude as the larger waves propagate faster.

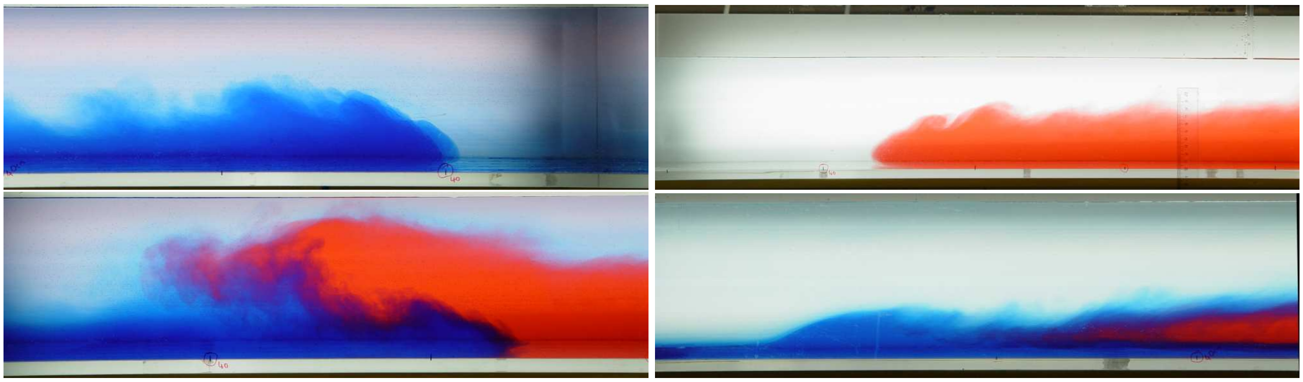


Figure 17. Colliding gravity currents with different densities illustrating the collision of two sea breezes with different temperatures behind them. See text for a description of the experiment.

Christie et al. (1979) and Clarke et al. (1981) concluded that the Morning Glory could be described as an internal undular bore similar to that described by Benjamin (1967). Using observed environmental profiles, Noonan and Smith (1985) found that weakly nonlinear theory was in reasonable agreement with the observed propagation speeds, although the theory gave horizontal wavelengths that were too large by a factor of two. Time dependent integrations of the BDO equation by Christie (1989) and Christie and Muirhead (1983a, 1983b) illustrated the asymptotic development of amplitude-ordered solitary wave families from smooth initial conditions. Detailed reviews of weakly nonlinear theories applied as to the Morning Glory can be found in two articles by Christie (1989, 1992). Egger (1985) investigated also the evolution of an initial disturbance into a solitary wave train, but in the context of the KdV equation.

Consider now the effect of the background easterlies on the medium through which the Morning Glory propagates. Although Morning Glory waves have large amplitude, linear theory has been used to describe, at least qualitatively, the structure of the wave guide on which they propagate (e.g. Crook 1986, Menhofer *et al.* 1997b). According to the linear theory for a two-dimensional sinusoidal wave propagating in a non-rotating, stably-stratified, Boussinesq atmosphere, the vertical wavenumber m is related to the environmental conditions through the expression

$$m(z)^2 = l(z)^2 - k^2$$

where

$$l(z)^2 = \frac{N(z)^2}{(U(z)-c)^2} - \frac{U_{zz}}{(U(z)-c)}$$

is the Scorer Parameter, k is the horizontal wavenumber, z is the geometrical height, N is the Brunt-Väisäla frequency, $U(z)$ is the component of the environmental flow normal to the wave and c is the horizontal phase speed. Small-amplitude gravity waves propagate vertically when m is real, but are evanescent when m is imaginary. Consequently, waves may be ducted when the environmental conditions, characterized by the vertical structure of the Scorer Parameter, restrict their propagation to a layer. One such configuration, thought to be important for the Morning Glory, is a stable surface-based layer permitting vertical propagation beneath a deep layer in which the waves are evanescent, preventing the loss of wave energy from the lower layer through upward propagation. Northeasterly Morning Glories propagate towards the southwest against an opposing low-level westerly and, hence, $U(z) - c > 0$. Crook (1988) investigated the conditions under which Morning Glory waves will be long-lived. They are when $N(z)^2$ decreases with height, when $U(z)$ increases with height, or when U_{zz} changes sign from negative in the stable surface layer to positive aloft. The last mechanism appears to be the one of most relevance to the Morning Glory. Menhofer et al. (1997a) calculated the distribution of the Scorer parameter from radiosonde soundings taken at Burketown on days on which Morning Glories were known to have been generated over the Cape York Peninsula, but failed to reach Burketown, and days on which Morning Glory were observed there. They showed that, although $U_{zz}/(U(z) - c)$ is mostly negative above the lowest few hundred metres, it is not uniformly so. Consequently, they concluded that the waves must be continuously forced, otherwise the waves would quickly attenuate as energy is lost through upward propagation. This finding is consistent with the recent numerical modelling study by Smith and Noonan (1989) who concluded that energy losses associated with the leakiness of the wave- guide in morning-glory wave disturbances may be at least partially offset by energy gains associated with the evolving mesoscale patterns generated by sea-breeze circulations.

The assumption of weak nonlinearity can be circumvented by solving the equations of motion numerically. Calculations of this kind include those of Clarke (1984), Crook and Miller (1985), Haase and Smith (1989), and Goler and Reeder (2004), all of which investigated the generation and propagation of undular bores and solitary waves as a gravity current or sea breeze moves into a surface-based stable layer. The key nondimensional parameter controlling the behaviour of the flow is $M = c_0/c_{gr}$. Here $c_0 = 2Nh/\pi$ is the phase speed at which the small amplitude waves propagate on the stable layer, c_{gr} is the speed of the gravity current, N is the Brunt-Väisäla frequency in the stable layer ahead of the gravity current, and h is the depth of the stable layer. For example, Goler and Reeder (2004) show that when the phase speed of these waves matches the westward propagation speed of an intrusive gravity current (the east-coast sea breeze), waves grow to large amplitude. This situation is shown schematically in Fig. 18a. When the intrusive gravity current (the east-coast sea breeze) propagates too fast relative to the waves, the waves do not amplify. For this perspective, solitary waves can be generated by a resonant coupling between the east-coast sea breeze and the disturbances that propagate on the shallow stable layer produced by the west-coast sea breeze.

Haase and Smith (1989) investigated the collision between a gravity current and a stable layer. They found that if the stable layer is sufficiently deep and/or strong so that the phase speed of waves on the layer is sufficiently large compared to the speed of the gravity current, a nonlinear wave disturbance forms and propagates ahead of the gravity current. This configuration is shown schematically in Fig. 18a. If the stable layer is too weak and/or shallow for this to be the case, the stable layer profoundly affects the gravity current head, which develops one or more large-amplitude waves enveloping the colder air (Fig. 18b). In this case the large-amplitude waves advect isolated regions of intruding cold air ahead of the main body of the gravity current. The first case (Fig. 18a) is said to be *subcritical* and the second case *supercritical* (Fig. 18b).

Haase and Smith *op. cit.* found that the transition from subcritical to subcritical flow occurred at a value of M around 0.7. The transition point is less than one because, according to weakly nonlinear theory, the phase speed of the waves which propagate on the stable layer increases with increasing amplitude. The number of waves is related to the relative depth of the stable layer. As the stable layer depth increases, the number of waves increases also, although their amplitudes decrease. Finally, as the cold pool has finite volume, the solitary waves may run ahead of it as depth of the cold air, and hence its speed, decreases with time (Fig. 18d).

Numerical simulations reported by Reeder et al. (2013) showed that the structure of the morning-glory disturbance produced depends on the strength of the collision between the asymmetric sea breezes, which in turn depends on the strength of the background easterlies. When the easterlies are comparatively weak, the sea breezes are relatively symmetric and their collision relatively violent. These results suggest that this case is subcritical in the sense that the stable layer provided by the west-coast sea breeze is sufficiently deep and strong to enable waves to propagate faster than the speed of the the east-coast sea breeze. The disturbance subsequently evolves into a series of amplitude-ordered solitary waves that runs ahead of the east-coast sea breeze as sketched in Fig. 18c.

In contrast, when the background easterlies are stronger, the sea breezes are asymmetric. In this case, the collision is comparatively gentle, with the east-coast sea breeze simply surmounting the west-coast sea breeze and running across the top of the cold air. These results suggest that this case is supercritical in the sense that the speed of small-amplitude waves supported on the layer of cold air advected onshore by the west-coast sea breeze is smaller than the typical wind speed behind the east-coast sea breeze (the configuration sketched in Fig. 18b.) These conclusions are supported by observation of Morning Glories at Mornington Island, far downstream from their point of origin.

9 Continental cold fronts in the Australian subtropics and tropics

The classical models for cold and warm fronts developed in the 1920's by the Bergen School of meteorologists have survived as important components of a model for the evolution of synoptic-scale low pressure systems in the middle latitudes. However, the reluctance of Australian meteorologists to analyze warm fronts over the Australian continent and unusual features of summertime cold fronts in southeastern Australia (some of them can be virtually cloud free) cast doubt on the utility of the Norwegian model for extratropical cyclones over Australian. Indeed, Lammert (1932) noted that cold fronts there tended to have much larger temperature contrasts to those in Europe, especially in summertime, and attributed this feature to the large temperature contrast between the hot continent and the maritime environment to the south that was dominated by the presence of Antarctica.

Recognition of the deficiency of the classical model of cold fronts in the region led to the establishment of a Cold Fronts Research Programme in Australia in the late 70's and early 80's (Smith et al. 1982b). A special focus was on the summertime "cool change", a kind of cold front that that brings relief to communities in the southern part of the continent after sometimes many days of scorching hot northerly winds from the continent. Three field experiments were organized as part of the research programme and these together with theoretical and numerical studies that the programme led to a new conceptual model of the cool change which differed considerably in detail from the classical Norwegian model. Unlike the classical cold front, many summertime cool changes were shallow and completely dry and it was evident that deep turbulent mixing over the strongly heated continent had an important role in the structure of these fronts. A review of the summertime cool change and a comprehensive list of references thereon is given by Reeder and Smith (1992).

Despite the progress in understanding the structure of the summertime cold front, which may be connected to a parent low over the Southern Ocean, there was still a reluctance by forecasters to analyse cold fronts very far into the interior of the continent. Rather, the equatorwards portion of the surface front was analysed as an inland trough line,

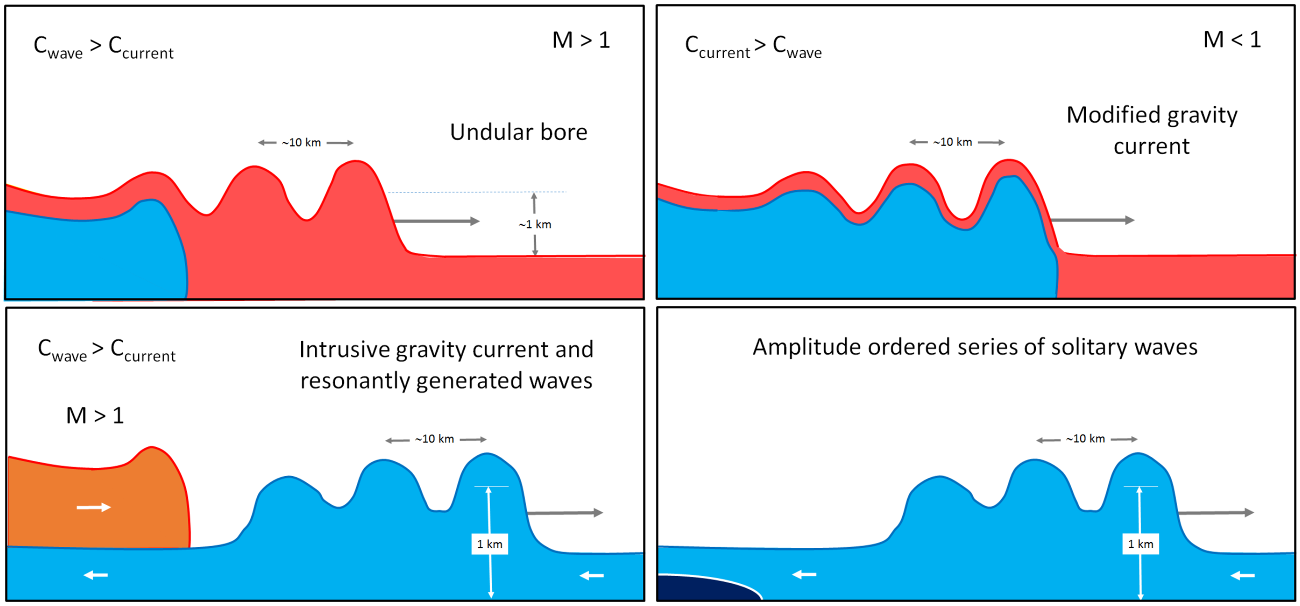


Figure 18. Conceptual model for the wave generation. (a) Subcritical case, $M > 1$, in which the waves propagate ahead of the gravity current. Here $M = c_0/c_{gr}$. Here $c_0 = 2Nh/\pi$ is the phase speed at which the small amplitude waves propagate on the stable layer, c_{gr} is the speed of the gravity current, N is the Brunt-Väisala frequency in the stable layer ahead of the gravity current, and h is the depth of the stable layer. (b)Supercritical case, $M < 1$, in which the waves remain bound to the gravity current. (c) Intrusive gravity current and resonantly generated waves, $M > 1$. (d) Freely propagating solitary waves after the cold pool has been exhausted. Based on Figure 1 from Locatelli et al. (1998).

sometimes extending as far north as the southern half gulf of Carpentaria. Even so, Lammert (1932) was aware that, on occasion, the cooler air may extend well into the tropics, even reaching the Gulf of Carpentaria (see her Fig. 5).

More recently, Berry et al. (2011a) objectively analysed the frequency of fronts globally in the European Centre for Medium range Weather Forecasts (ECMWF) ERA-40 reanalysis. Their detection method is based on the wet-bulb potential temperature at 850 mb. Cold fronts over Australia are most common in the spring and summer. Although there are distinct geographical maxima lying in the southwestern and southeastern parts of the continent, cold fronts are analysed across the entire continent, including the tropics. In contrast, on the rare occasions that warm fronts are analysed, they are confined to the southern coastline principally during summer. Presumably these analysed warm fronts are associated with the offshore advection of warm continental air by northerly air streams and are not classical Norwegian warm fronts.

9.1 An early field experiment

An interest in cold fronts at subtropical and even tropical latitudes was awakened by attempts to determine the origin of southerly Morning Glories. An analysis of synoptic conditions for the occurrence of southerly Morning Glories observed during field experiments in the early 80's pointed to the likely role of the inland heat trough as a ridge of high pressure, preceded, perhaps[1], by a cold front, extends eastwards across the continent (Smith et al. 1986). These findings raised fundamental questions concerning the structure and dynamics of the inland trough, the structure and dynamics of subtropical cold fronts, and the mechanism of interaction between an advancing frontal trough and the inland trough. These are important questions vis-á-vis the meteorology of the Australian subtropics, but up to the late 80‘s they had received relatively little study, partly because the routine data base across the sparsely populated interior of the Australian continent was totally inadequate for this purpose.

To help answer the foregoing questions, a small pilot field experiment was organized in September 1988 to obtain data on the inland heat trough in central and northern Australia (Smith and Ridley 1990). The vertical structure of three fronts was investigated as they passed over Mount Isa (21^oS, 139^oE), which in each case lay near the northern limit of a synoptic cold front and the southern limit of a semi-permanent pressure trough to the northwest. Figure 19 shows height-time cross-sections of potential temperature, θ, and of equivalent potential temperature, θ_e, at Mount Isa for the first event and of θ for all two other events.

The three cold fronts had some very similar characteristics. The front and trough were originally completely separate features, but the approach of the front from the west appeared to result in the gradual amalgamation of the two in the vicinity of Mount Isa. This front/trough system was contained in all cases between a ridge of high pressure along the Queensland coast and an intensifying ridge across central Australia. These characteristics are consistent with observations of the synoptic conditions conducive

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[1] At that time, cold fronts were not usually analysed so far equatorwards.

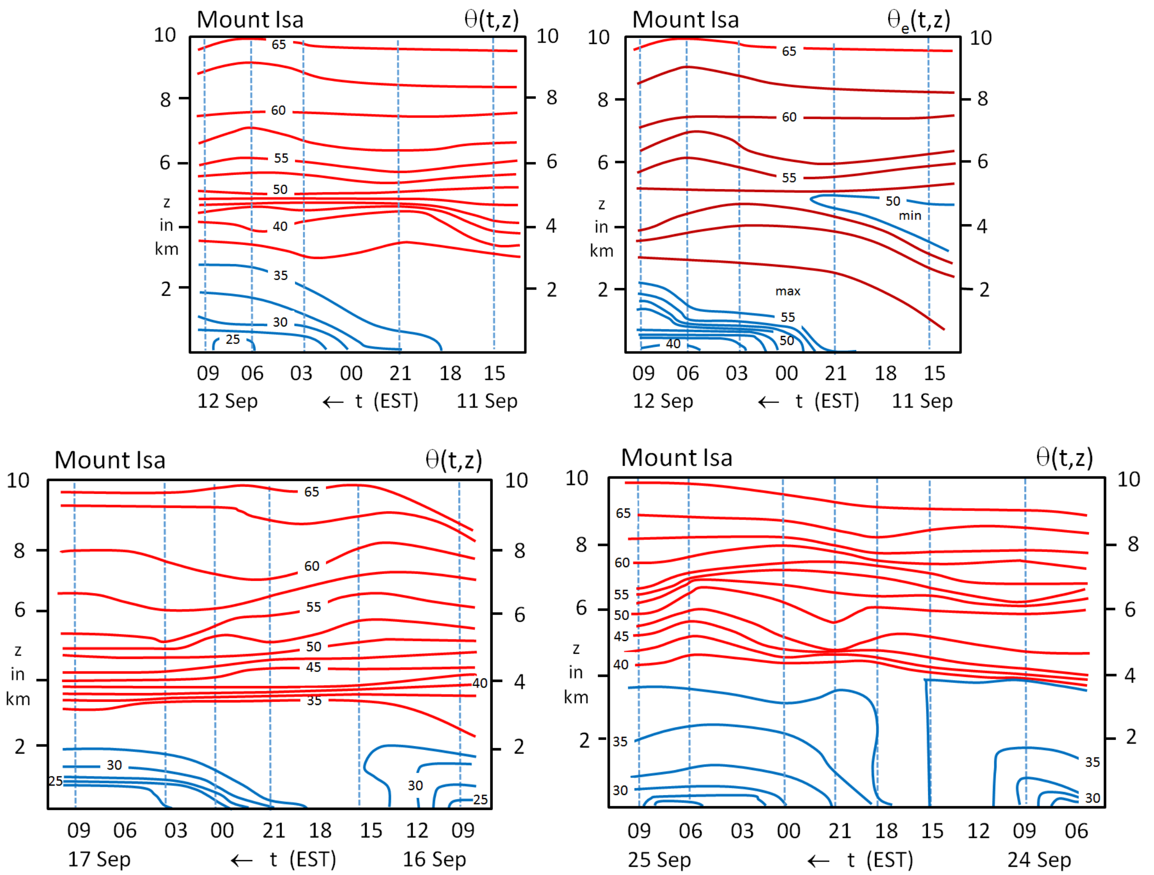

Figure 19. Height-time cross-sections of (a) potential temperature θ and (b) equivalent potential temperature θ_e at Mount lsa for Event 1 and of θ for (c) Event 2 and (d) Event 3. Heights are above ground level and isopleths are labelled in deg. C.

to the formation of southerly Morning Glories in the gulf area (see section 3 above).

9.2 The Central Australian Fronts Experiment 1991

The Central Australian Fronts Experiment (CAFE) was organized to provide a more comprehensive data set on subtropical cold fronts that could be used to answer some of the basic questions about frontal structure and behaviour and to help confirm or reject predictions obtained from model simulations. The experiment ran from 7 September until 4 October 1991 and documented three cold fronts over central and northeastern Australia in unprecedented detail, with data obtained from a greatly enhanced surface observing network, a boundary-layer wind profiler as well as serial upper-air soundings (a map of the observational network is shown in Fig. 20). Data on the surface energy balance were obtained also. The findings of the experiment are reported by Smith et al. (1995), Reeder et al. (1995), and Deslandes et al. (1999).

9.3 The structure of dry subtropical cold fronts

A common feature of all six fronts documented during CAFE and of the pilot experiment (pre-CAFE) was that they were dry, shallow (around 1 km deep), and moved into a deep (around 4 km) convectively-well-mixed boundary layer. During the night, the well-mixed layer was terminated below by a strong, but shallow radiation inversion. One of the fronts initiated major dust storms across central Australia.

The synoptic environment of these fronts was similar to that of the summertime “cool-change” of southeastern Australia with frontogenesis occurring in the col region between the two subtropical anticyclones, relatively far from the centre of the parent cyclone (Reeder and Smith 1992, Fig. 21). A unique feature of the region is the presence of a heat trough over northeastern Queensland with which the frontal trough eventually merges. Generally, the frontal passage is followed by strong ridging from the west.

The data obtained during the CAFE experiment highlighted the large diurnal variation of frontal structure associated with diabatic processes. The fronts were difficult to locate during the late morning and afternoon when dry convective mixing was at its peak, but developed strong surface signatures in the evening as the convection subsided and a surface-based radiation inversion developed. Moreover, there appeared to be a ubiquitous tendency in the early

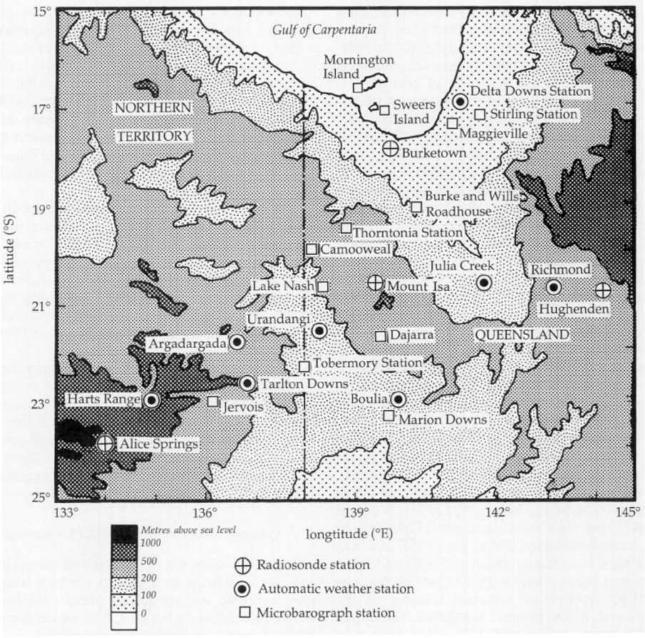

Figure 20. Map of the observational network for the 1991 CAFE experiment. From Smith et al. (1995).

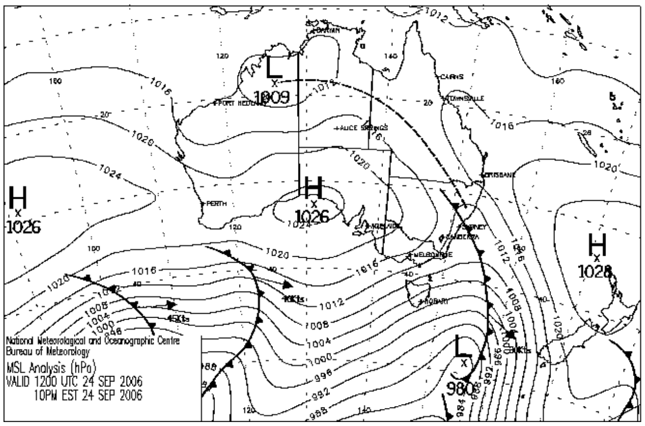

Figure 21. A typical mean sea level chart with a trough line (indicated in the analysis by a dashed line) extending from a heat low over Western Australia around the northern perimeter of an anticyclone that is crossing the continent to a cold front that is crossing the southeastern part of Australia. Although not analysed as such, the trough line is essentially a shallow cold front.

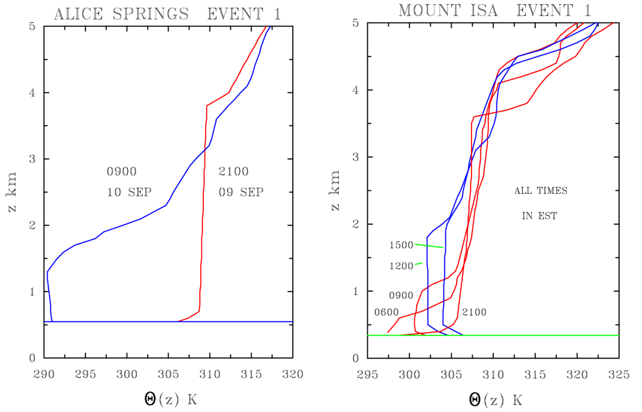

Figure 23. (a) Vertical profiles of potential temperature and virtual potential temperature, $\theta(z)$ and $\theta_v(z)$, in the prefrontal and post-frontal air mass at Alice Springs for the first event during CAFE. The frontal passage at Alice Springs occurred at 0355 EST 9 September. (b) Vertical profiles of potential temperature $\theta_v(z)$ in the prefrontal and postfrontal air masses at Mount lsa for the first event during CAFE, which arrived at Mount Isa at 0940 EST I 0 September. The soundings at 2100 EST 9 September and at 0600 and 0900 EST 10 September are therefore about 13, 3, and I h before the frontal passage, respectively. The soundings at 1200 and 1500 EST are about 2 and 5 h after the frontal passage. Adapted from Smith et al. (1995).

morning for the formation of non-linear wave-like or bore-like structure at the leading edge of the frontal zone as the inversion strengthened. In each case, as the wave/bore developed, it was observed to propagate ahead of the air mass change on the pre-existing inversion. Such behaviour was exemplified by the data for the first two events during CAFE. In the latter case, the data are unique in providing the first clear evidence of the formation of a southerly Morning Glory bore-wave in the Gulf of Carpentaria region from a cold front in the south. The passage of a bore brings a strong, but temporary wind surge at the surface accompanied by a sharp pressure jump. These are followed by a series of wind and pressure oscillations with a period of 10-15 min, before the steadier post-frontal airflow is established. There is no air mass change with the passage of the bore, but the vigorous turbulence that accompanies it may lead to a breakdown of any shallow radiation inversion that exists, leading to an actual *rise* in surface temperature.

9.4 The Central Australian Fronts Experiment 1996

The Central Australian Fronts Experiment 1996 (CAFE96) was the third in a series of field experiments designed to document the behaviour of subtropical continental cold fronts during the late dry season. Its central aim was to investigate the structure and dynamics of subtropical cold fronts that affect central Australia and prior to their evolution into bore-like disturbances as they approached the Gulf of Carpentaria region. The experiment was carried out in the region between Giles in Western Australia and Burketown in northwestern Queensland from the end of August until early October 1996. A special network of surface measuring stations was installed in the normally data void region between Yulara and Mount Isa and between Mount Isa and Burketown. These included fourteen AWSs that were deployed along a southwest/northeast oriented line between Giles and the lower Cape York Peninsula.

Seven fronts were documented in detail during CAFE96 and, by and large, they confirmed the conclusions from CAFE91. The results of the experiment are presented in Reeder et al. (2000), which focused principally on three frontal systems: Events 3, 4 and 6. Events 4 and 6 were

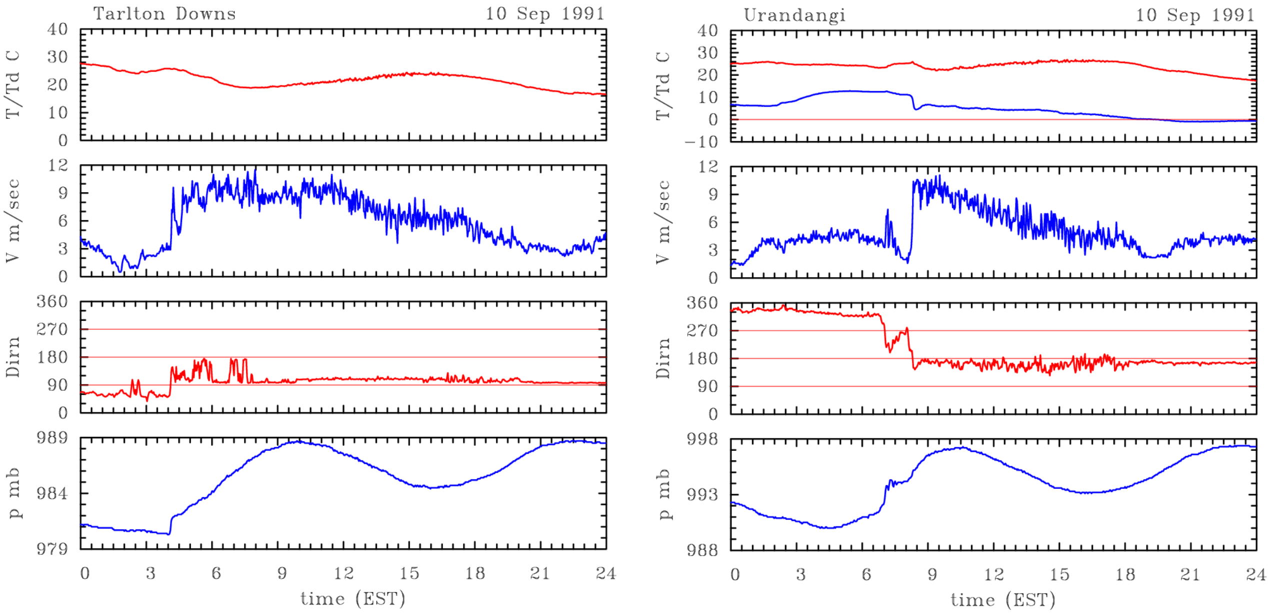

Figure 22. Surface data from Tarlton Downs and Urandangi (for location see Fig. 2) for the first frontal passage during the CAFE experiment. The panels show from top to bottom: the temperature in deg. C, the water vapour mixing ratio in gm/kg, the wind speed in m/sec, the wind direction, and the pressure in mb (the dew point temperature was unavailable at Tarlton Downs). Note the undular bore-like disturbance that occurs about 0700 Eastern Australian Time (EST). Its passage is marked by sharp jumps in pressure and temperature, a sharp change in wind direction from WNW to SW and a marked freshening of the wind. The temperature rise is a result of the destruction of the shallow nocturnal radiation inversion as the wind freshens. The passage is followed by regular fluctuations in pressure and in wind speed and direction for three quarters of an hour. The passage of the cold front, itself, is indicated by the sharp increase in wind speed and a further backing of the wind about 0815 EST. Following this, the temperature begins to decline steadily, the pressure begins a steady rise and the mixing ratio falls sharply. Adapted from Smith et al. (1995).

emphasized because aspects of their structure and evolution were a little different from the previously reported paradigm. For example, of the 14 fronts documented in detail during CAFE96, CAFE91 and pre-CAFE, only these events were detected during the late morning or afternoon. Moreover, Event 6 decayed over central Australia, only to re-intensify two days later over the northeastern part of the continent. Unlike most of the 14 fronts studied, Events 4 and 6 were accompanied by severe weather over eastern Australia. Event 4 re-intensified during late afternoon and subsequently crossed the eastern half of the network. The front continued to intensify overnight, generating a spectacular family of southerly bore waves (or southerly Morning Glories). By the end of the event, a zone of strong equivalent potential temperature gradient stretched across the whole of northern Australia.

Event 6 developed in a broad, slow-moving, extratropical cyclone that advanced across southern Australia. The system had the structure of classical mature extratropical cyclone and was accompanied by a cold front and strong warm front. Recent research (Berry et al. 2011a, see Fig. 3) suggests that warm fronts are uncommon in the region, but Event 6 is an example of one. Warm fronts generally lie poleward of the low and hence south of the Southern Ocean storm track. The cold front, itself, strengthened and moved northeastwards across central Australia in the early hours of 28 September 1996, arriving at Santa Teresa at 0730 CST and at Alice Springs at 1010 EST (0940 CST). However, as the daytime turbulent mixing increased, the front stalled and retreated back through Alice Springs at 1125 CST, bringing with it northwesterlies and blowing dust. The front retreated through Santa Teresa about 1330 CST. It subsequently weakened and there is little clear evidence that it crossed the network again. While it is probably quite common for the position of subtropical cold fronts to oscillate back and forth in response to the daytime turbulent mixing, Event 6 is the only documented example of which we are aware.

It must be emphasized that we do not consider the leading edge of the front to be a material surface being advected back and forth across the centre of the continent. Rather, the leading edge of the front is generally much shallower than the depth of the daytime mixed layer and we envisage that the nose of the front is eroded by turbulent mixing in the vertical, leaving a broadscale horizontal temperature gradient. At night, once the (buoyantly-generated) turbulent mixing subsides, the large-scale pattern of deformation acts to re-establish a strong cross-frontal temperature gradient. The dynamics of fronts like Event 6 is largely unknown and is a topic for further research. As the ridge built across the continent, strong frontogenesis developed over northeastern Australia on 30 September 1996. The surface pressure pattern implied very strong geostrophic deformation over central and northern Queensland with the

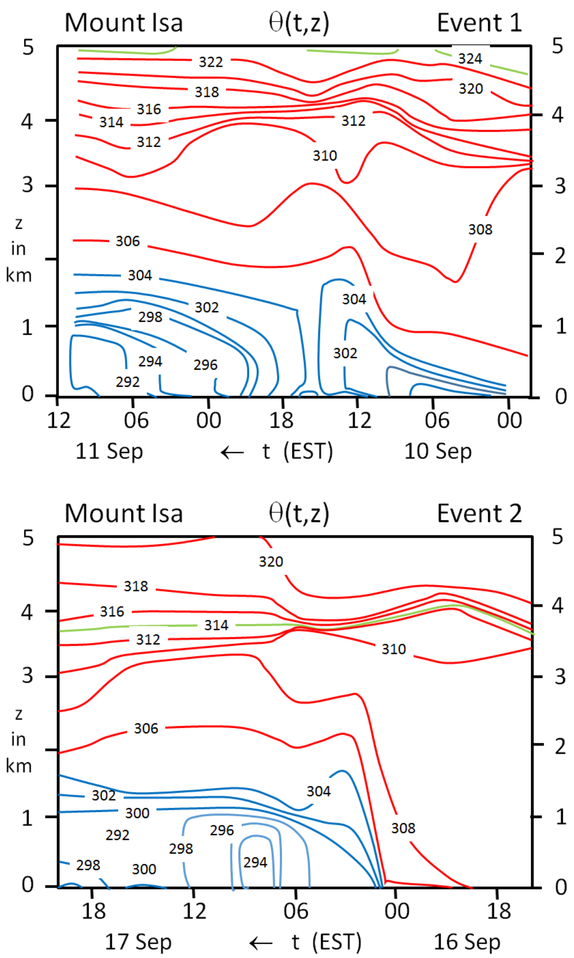

Figure 24. Time-height cross sections of potential temperature at Mount lsa for (a) CAFE Event I and (b) CAFE Event 2. Adapted from Smith et al. (1995).

dilatation axis along the trough axis. Event 6 re-formed locally and crossed the northeastern part of the observational network during the late morning of 30 September.

The structure and evolution of Event 3 was typical of those subtropical fronts reported previously. It strengthened and accelerated during the evening of 11 September 1996, and crossed the observational network during the night and early morning hours. Strong near-surface warming followed the passage of the front. This warming was detected in the enhanced satellite imagery and confirmed by surface measurements.

The study Reeder et al. (2000) emphasized the utility of low-level cyclonic relative vorticity in analyzing fronts over continental Australia. Although not commonly used in frontal analysis, low-level cyclonic relative vorticity has proved to be reliable indicator of frontal position even when the front is affected by strong spatial and temporal changes in sensible heating. While the fronts in the Australian subtropics often show little continuity in most fields (such as temperature), they can be traced continuously in the fields of vorticity and equivalent potential temperature.

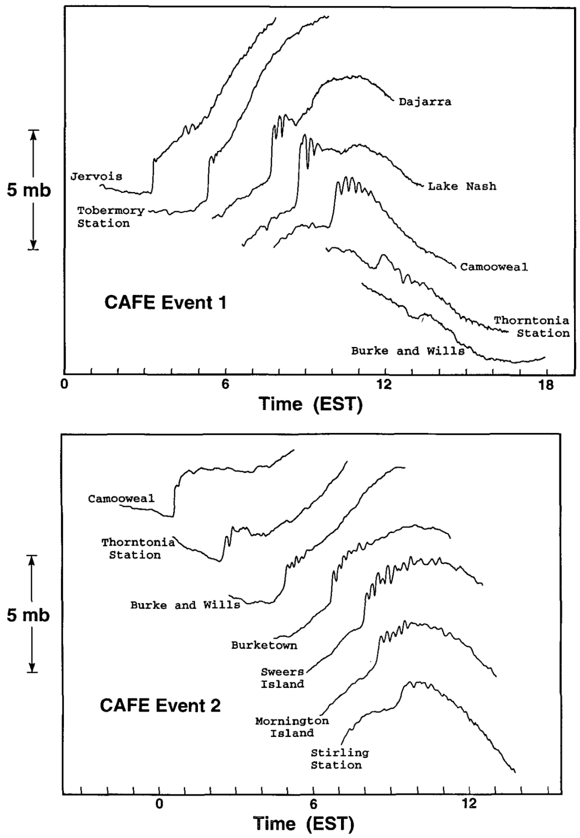

Figure 25. (a) Surface pressure signatures recorded at microbarograph stations at and to the south of Burke and Wills Roadhouse during the first CAFE event. The signatures are arranged sequentially with the southwesternmost station (Jervois) at the top and northeasternmost (Burke and Wills) at the bottom. Note the development of a wavelike signature as the disturbance moves northeastward, prior to its demise northeast of Camooweal. (b) Surface pressure signatures recorded at microbarograph stations at and to the northeast of Camooweal during the second CAFE event. As in Fig. 11, the signatures are arranged sequentially. Again, note the development of an undular-bore-like signature as the disturbance moves northeastward during the night and early morning. From Smith et al. (1995).

In general, the results of CAFE96 confirmed the conclusions drawn from the two previous experiments, but they raise a number of theoretical questions concerning the effect of turbulent mixing on the evolution and progression of subtropical cold fronts. Idealised modelling of cold fronts with turbulent boundary layers has shown that the net of effect of the boundary layer is to weaken the front relative to a front without a boundary layer. Moreover, the cross-front ageostrophic wind increased and the pre-frontal updraught strengthened (Reeder and Smith 1986, Tory and Reeder 2005, Muir and Reeder 2010). The results are qualitatively similar to the effect of adding an Ekman boundary layer.

When surface sensible heating and cooling is included in these idealised calculations (Reeder and Tory 2005, Muir and a Reeder 2010), the fronts weaken during the day and strengthen at night as the ageostrophic wind in the boundary layer accelerated in close agreement with observation (e.g. Smith et al., 1995; Reeder et al., 2000). Fronts slow or even retreat during the day and surge towards the warm air once the daytime mixing ceased in idealised calculation. However, unlike fronts over central Australia, the the depth of the boundary layer is small compared to the depth of the cold air in these idealised calculations. The dynamics of fronts with depths comparable to that of the boundary layer has not been investigated, although this is the case of most relevance to subtropical cold fronts.

9.5 Numerical simulations

Thomsen et al. (2009) investigated the effect of the diurnal cycle on the evolution of cold fronts in the Australian subtropics in two high-resolution numerical simulations. The simulations are made using the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model (MM5) with the initial and boundary conditions taken from the operational analyses of the European Centre for Medium Range Weather Forecasts. These simulations were compared with the observations of two cold fronts taken during the 1991 CAFE experiment. The simulations showed a number of features that have been suspected, but never confirmed or quantified.

- Although the wind field in the boundary layer is frontogenetic, daytime turbulent mixing is strongly frontolytic, which accounts for the weakening and deceleration of the fronts during the late morning and afternoon when convective mixing in the boundary layer is most vigorous.
- When the mixing subsides in the early evening, the low-level winds increase along with the deformation and convergence, leading to a strengthening and acceleration of the fronts.
- Bore-like disturbances are generated during the early hours of the morning as the nocturnal inversion strengthens. These bores propagate ahead of the front, developing a series of large-amplitude waves at their leading edge. The results were in support of idealized simulations of gravity currents moving into a surface-based stable layer (Haase and Smith 1989a,b).

10 Heat lows and heat troughs

Heat lows or heat troughs are prominent climatological features of many arid land areas of the world during the warmer months, especially at low latitudes where insolation is strong. These areas include northwestern and northeastern Australia. A list of pertinent references is given by Rácz and Smith (1999). These systems are sometimes referred to as thermal lows or thermal troughs, respectively, and they are comparatively shallow disturbances, generally extending up to the depth of the convectively well-mixed layer (typically 3-4 km).

Heat lows and heat troughs have many dynamical features in common. The distinction in a surface isobaric chart can depend on the isobar spacing, where the former has at least one closed isobar while the latter has the form of an open wave. Both types of disturbance may be thought of as localized regions of enhanced low-level cyclonic relative vorticity that are linked to horizontal gradients of diabatic heating.

Our own work was motivated by the desire to understand the inland heat trough over Queensland and the heat lows of central and northwestern Australia. As noted in section 9.1, the inland heat trough over Queensland appears relevant to understanding the origins of southerly Morning Glories. Figures 6, 9 and 19, for example, show mean sea level isobaric charts of the Australian region with a heat low over northwestern Australia and a heat trough (marked by the dashed line) running inland from the low to a frontal trough over southeastern Australia.

10.1 The dynamics of heat lows: basic studies

Motivated by our observations over northeastern Australia, Rácz and Smith (1999) carried out idealized numerical model simulations to investigate the evolution and structure of a heat low over a square flat island surrounded by sea. Two important findings were:

- The heat low has a minimum surface pressure in the late afternoon or early evening following strong insolation of the land, while the relative vorticity is strongest in the early morning hours following a prolonged period of low-level convergence. Thus the heat low is not approximately in quasi-geostrophic balance.
- The low-level convergence is associated with the sea breeze and later with the nocturnal low-level jet.

These findings were in accord with observed features of the heat lows over Australia (e.g. Preissler et al. 2002) and are supported by observations of the Saharan heat low. Indeed, they go some way also to explaining the observed diurnal cycle of the West African monsoon circulation (Parker et al. 2005 and references).

Rácz and Smith (1999) investigated also the effects of differing land area and Coriolis parameter on various aspects of the heat low, but gave little attention to the overlying anticyclone. In a subsequent paper, the two authors extended their model to examine the effects of orography on heat low formation and structure (Reichmann and Smith, 2003) and the model was extended further by Spengler et al. (2005) to examine the effects of simple background flows on the heat low.

The cycle of diabatic heating and cooling of the atmosphere in the numerical model was accomplished using the Mellor-Yamada $2\frac{1}{4}$-parametrization scheme for the boundary layer (Mellor and Yamada, 1974) in association with surface heating or cooling. After long integration times, this scheme leads to unrealistic mixed-layer depths because the only mechanism for cooling to oppose the et heating of the atmosphere is that which occurs in a shallow layer adjacent to the surface. In an effort to remove this limitation, in their study of orographic effects, Reichmann and Smith (2003) incorporated the radiation scheme proposed by Raymond (1994) into the model. This scheme is based on a grey atmosphere approximation and allows the atmosphere to cool, thereby preventing the long-term growth of the mixed layer.

10.2 Effects of a simple background flow

Calculations for a heat low in simple background flows were carried out by Spengler et al. (2005). Like the case without a background flow, the flow shows a significant diurnal variation in which the sea-breeze circulations are the prominent feature during the daytime and the nocturnal low-level jet is the prominent feature at night. If the land area is large enough so that the sea breezes do not cover it entirely during the diurnal cycle, strong convergence associated with the low-level jet leads to the formation of intense, but shallow, cold fronts along the inland boundaries of sea-breeze air. These fronts decay rapidly after sunrise when surface heating leads to renewed vertical mixing, which destroys the low-level stable layer.

The presence of a uniform easterly flow leads to the formation of a west-coast trough, similar to the situation commonly observed over Western Australia. The trough broadens during the day due to the heating of the land, while at night it sharpens and again frontogenesis occurs at low levels near the leading edge of the sea breezes to form shallow cold fronts. In this case here is an east-west asymmetry in the sea-breeze circulations: the cool air behind the west-coast sea breeze is shallower than that behind the east-coast sea breeze, but the vertical circulation associated with the west-coast sea breeze is deeper. The east-coast sea-breeze front penetrates further inland, but is more diffuse and is recognizable more by its signature in the relative vorticity than by that in the horizontal temperature gradient.

The presence of a horizontal shear-flow leads to the deformation of the heat trough, a process that appears to play an important role in the formation of cold fronts over central Australia. Again the calculations show the formation of shallow fronts over the land during the night, which frontolyse rapidly after sunrise. Despite the idealized nature of the calculations, the associated patterns of low-level vorticity, divergence and horizontal temperature gradient that develop overnight show remarkable similarity to those observed over central Australia.

10.3 An improved numerical model

During the course of the foregoing study, Thomas Spengler discovered some errors in the model initialization and in the numerical implementation of the radiation scheme by Reichmann and Smith (2003) and also errors in Raymond's (1994) paper. The errors in the initialization were found to have a negligible effect on the results presented by Reichmann and Smith and those made in the implementation of the radiation scheme had only a small impact. However, their existence motivated the development of a new idealized model with an improved radiation scheme (Spengler and Smith 2008). This new model was run with a higher horizontal resolution than the original version and used to investigate additional dynamical aspects of the structure and evolution of a heat low over a subcontinental- or continental-scale circular island. These aspects included:

- the development of an upper-level anticyclone, and
- the degree to which the cyclonic and anticyclonic circulations are in gradient wind balance.

Figure 26 shows height-radius cross sections of potential temperature and tangential wind speed in the late afternoon (1700 h) on day 11 in the calculations for a circular island of radius 800 km. At this time, the effects of insolation are near a maximum. The potential temperature field shows a mixed layer (characterized by the depth of the region of uniform potential temperature at the centre of the domain of just over 4 km, a value that is typical of inland soundings across central Australia. The low-level winds are cyclonic and relatively light at this time, not exceeding 4 m s^{-1}. The most striking feature of the azimuthal wind field at 1700 h is the anticyclone, which has a maximum wind speed of over 12 m s^{-1} at heights between about 2 and 3 km. Interestingly, this anticyclone extends throughout much of the troposphere, although it decreases in strength with height in the upper troposphere. This decay is consistent with slightly cooler air overlying the heat low, assuming thermal wind balance.

In a mean sense one can distinguish between distinct patterns of the tangential flow component in the heat low:

- between midnight and noon, when the low-level cyclone is strongest, and
- between noon and midnight when it is much weaker.

These differences reflect the strong turbulent mixing of momentum in the mixed layer over land during the afternoon, which leads to a significant weakening of the cyclone, and the formation of a strong low-level jet at night, which re-amplifies the cyclone circulation.

The calculations showed that the upper-level anticyclone extends through much of the troposphere, but has its maximum strength in the lower troposphere, just offshore. It exhibits relatively little diurnal variation when the heat low reaches its mature stage; much less so than the low-level cyclone. The anticyclone develops steadily over a period of a few days and is associated with the return (offshore) branch of the sea-breeze circulation in the lower troposphere and a slow diurnal-mean outflow in the middle and upper troposphere. The outflow at upper levels may be interpreted as a mean drift induced by upward-propagating inertia-gravity waves that are initiated by the

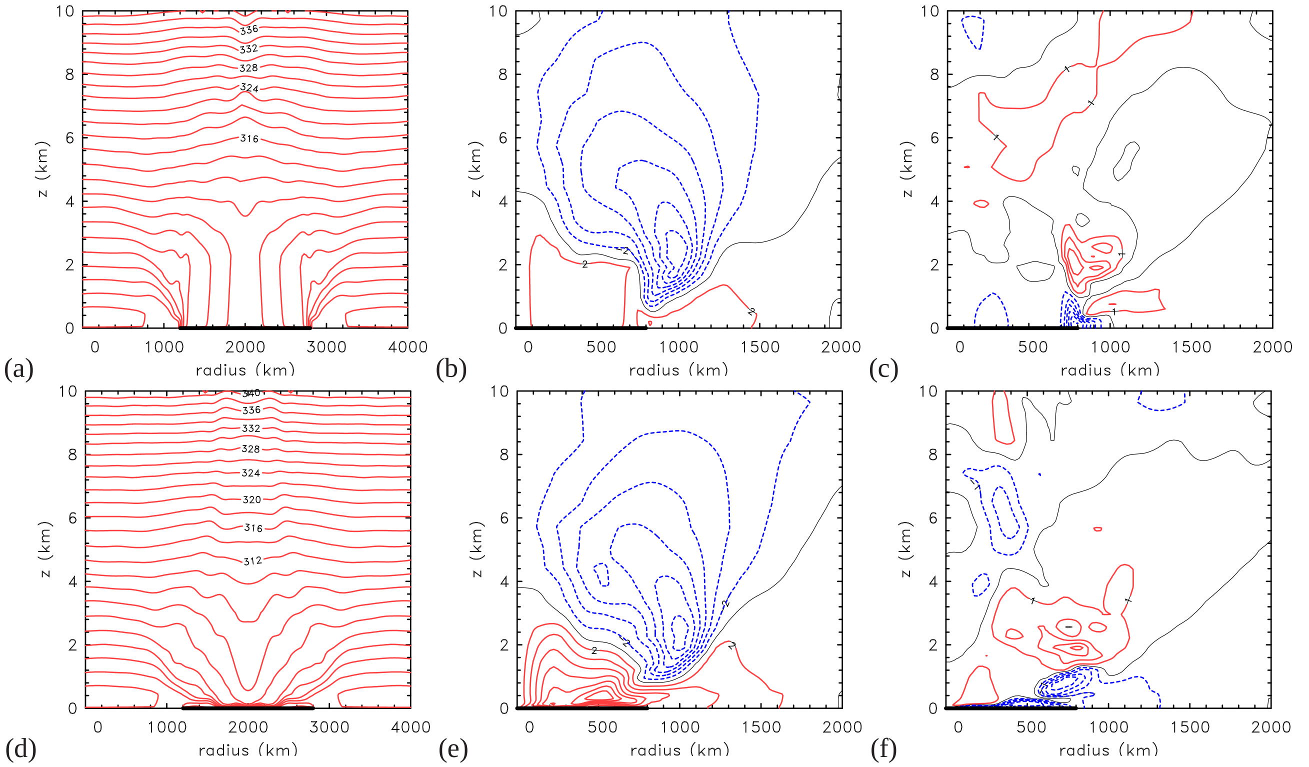

Figure 26. Height-radius cross sections of potential temperature (left panels), tangential wind component (middle panels), and radial wind component (right panels) at selected times (upper panels 1700 h, lower panels 0500 h) during the mature stage of the calculation (day 11). Contour interval for potential temperature 2 K; for tangential wind 2 m s^{-1}, solid lines indicate cyclonic and dashed lines anticyclonic circulation; and radial wind speed 1 m s^{-1}; solid lines indicate outward and dashed lines inward flow. Only half of the domain is shown in the case of the wind fields. The thick black line along the abscissa shows the region of land. (From Spengler and Smith 2008).

inland-penetrating sea-breeze front during the afternoon and evening.

Spengler and Smith showed that there is a strong analogy between the dynamics of heat lows and to certain aspects of the dynamics of tropical cyclones, which have a warm core, a shallow unbalanced boundary layer, and which are surmounted also by an anticyclone. Principles governing the absolute angular momentum budget are the same as those relating to the tropical cyclones (Smith *et al.* 2014) and to the zonal-mean flow over Antarctica (Egger 1985). Implications of these principles for obtaining a realistic steady state in long-term integrations of axisymmetric models were discussed.

10.4 The effects of orography

In a subsequent paper, Smith and Spengler (2010) investigated orographic effects on the dynamics of heat lows, again in in an idealized flow configuration. The behaviour of the heat low that forms over a plateau-like orography on a circular island is compared with that when the island is flat, and that when the plateau is surrounded by land instead of sea. In all cases, a broad-scale, negative radial gradient of potential temperature forms in the daytime mixed layer over land. The presence of orography enhances the broad-scale baroclinicity over the orographic slope due to the identical heating of a column of air with a reduced mass, i.e. lower surface pressure. In the absence of sea, the baroclinicity is solely confined to the slope of the orography.

The broadscale potential temperature gradient results in an overturning circulation in the lowest few kilometres, which is separate from the shallower and more intense sea breeze circulation in the island cases. The presence of orography leads to a stronger overturning circulation via enhanced baroclinicity. In the case without sea, both the overturning circulation and tangential circulation are closely tied to the orography. The overturning circulation advects absolute angular momentum surfaces inwards to spin up the low-level circulation, despite some frictional loss of angular momentum enroute. During the night, radiative cooling over the land leads to a strong nocturnal low-level jet that amplifies the spin-up process. During the daytime, the cyclone weakens as the angular momentum is convectively mixed through a deep layer.

11 Dry lines

Perhaps the most striking feature of the low-level seasonal climatologies of the Australian region the diurnally-varying airmass boundaries in the northern part of the continent (Arnup and Reeder 2007). As an example, Fig. 27(a,b) shows the seasonal average mixing ratio gradient and potential temperature at 925 mb for September-October-November (SON) at 1600 EST and 0400 EST. This climatology is based on climatologies of 3 hour forecasts from the high-resolution Australian Bureau of Meteorology's Limited Area Prediction Scheme (LAPS) from 2000 to 2003. The largest moisture gradients lie on the boundary between the moist tropical and dry continental air masses. Although the coastal gradient is relatively weak compared to the strong gradient that marks the dry line, the coastal gradient occurs every day in the same geographical location, and consequently masks the signal of the dry line, which is less frequent, more intense, and more variable in its location. For this reason, the points where the mixing ratio gradient is less than 5.0×10^{-5} g kg^{-1} m^{-1} are excluded from the calculation of the average. This conditional average effectively filters the coastal gradient from the averaged fields. During the day the sea breeze advects tropical maritime air inland, producing a diffuse strip of moist air around the coastline. Subsequently the dry line develops overnight from the weak boundary between the tropical and continental air masses. Like the sea breeze circulation, the dry line is strongest in spring and summer.

In contrast to the dry line of the Great Plains in the United States, the Australian dry line strengthens overnight. (For a comparison of the Australian and Great Plains dry lines, see Arnup and Reeder 2009). This nocturnal strengthening is part of the dramatic diurnal rearrangement of the low-level flow discussed in section 10. For example, Fig. 27(c,d) shows the average ageostrophic wind and divergence at 925 mb and MSLP for SON at 1600 EST and 0400 EST. During the day, surface heating leads to the formation of an extensive heat trough across northern Australia. The trough is centred to the northwest of the continent and extends eastwards, poleward of the Gulf of Carpentaria to the base of Cape York Peninsula. Although not shown here, the location of the trough shifts from 20^{o}S in summer, to well equatorward of Australia in winter, as the latitude of maximum of solar insolation moves with the seasons (Arnup and Reeder 2009). At night, radiative cooling leads to the development of a stable layer in which the surface friction is reduced. As surface winds readjust to a new balance of forces, air accelerated toward low pressure, increasing the low-level convergence in the heat trough. Convergence acts to strengthen the background moisture gradient in the region of the heat trough.

The development of the dry line poleward of the Gulf of Carpentaria and the southerly Morning Glory are closely related. Both form overnight when the inland airmass accelerates down the pressure gradient over northern Australia and meets the sea breeze propagating inland from the Gulf of Carpentaria. The southerly Morning Glory occurs when the pressure gradient is sufficiently strong to force the inland airmass to either collide with or ride over the sea breeze (e.g. Thomsen et al. 2009). Presumably the range of possibilities sketched in Fig. 18 are applicable to the interaction of the subtropical cold front and stable layer associated with the sea breeze from the gulf. When the speed of the surging inland airmass matches the phase speed of waves developing along the sea breeze, an undular bore-like wave propagates ahead of the dry line into the Gulf of Carpentaria. It is principally strong ridging over central Australia that produces the strong meridional temperature and pressure gradients required for the formation of the southerly Morning Glory, however these gradients are enhanced by the heat trough. It follows that the southerly Morning Glory and the dry line frequently form in the same location.

12 Outstanding questions

Although it is more than three and a half decades since the first Morning Glory expedition, and much has been learnt, the difficulty in taking observations in the northern Australia means that there are still aspects of the Morning Glory about that remain uncertain. These include the following.

- The nature of the wave guide as dry, daytime convection over land resumes remains to be determined. Presumably, as the inversion is eroded from below, the wave guide becomes progressively thinner and more elevated. Such a structure may be very similar to the wave guide over the ocean off northwestern Australia (e.g. Birch and Reeder 2013).
- The details of the collision of the sea breezes are perhaps the least well understood aspects of Morning Glories. Although there are no observations of the birth of a Morning Glory, numerical modelling suggests that the strength of the background easterlies controls the type of disturbances produced in the gulf region in two ways. First, the strength of the background easterlies affects the force of collision between the east-coast and west-coast sea breezes from which Morning Glories evolve. Are Morning Glories generated resonantly when the east coast sea breeze is much deeper and warmer than the west coast sea breeze? Conversely, when the sea breezes are more equal in depth and temperature, is the collision violent and does the disturbance produced evolve into a series of amplitude ordered-solitary waves? Second, the strength of the easterlies affect the structure of the medium through which the disturbance subsequently propagates and the speed at which the disturbance propagates and evolves downstream.
- Although southeasterly Morning Glories have been observed in satellite imagery, their dynamical origins are unknown.

Further outstanding questions concern the degree to which the dry season phenomena described here initiate or focus convection during in the wet season, and the degree to which these phenomena are themselves modified by convection.

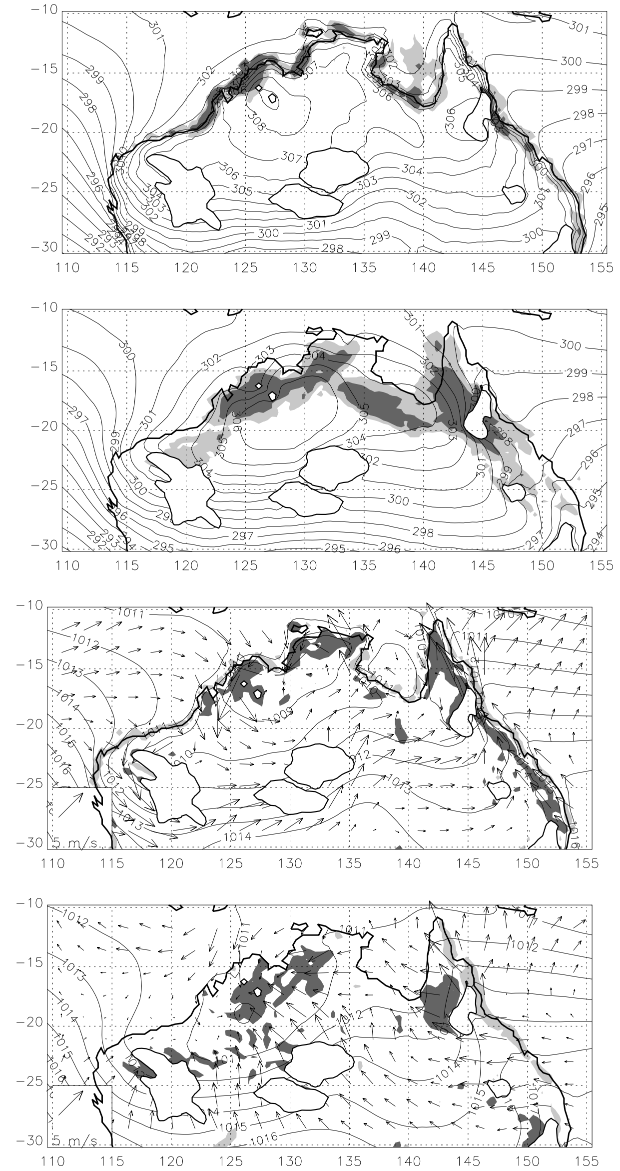

Figure 27. Average mixing ratio gradient and potential temperature at 925 mb for SON 200003 at (a) 1600 and (b) 0400 EST. The calculation of the average mixing ratio gradient excludes all model points in the LAPS 3-h forecasts where the mixing ratio gradient is less than 5.0×10^{-5} g kg^{-1} m^{-1} and is averaged over the number of days per seasonal average. Light shading indicates gradients greater than 0.2×10^{-5} g kg^{-1} m^{-1}; dark shading indicates gradients greater than $0.4 \times 10^{-5}5$ g kg^{-1} m^{-1}. The temperature contour interval is 1 K. Average ageostrophic wind and divergence at 925 mb and MSLP for SON 2000-2003 at (c) 1600 EST and (d) 0400 EST. The wind reference vector is located to the bottom left of each panel. Light shading indicates divergence greater than 1×10^{-5} s^{-1}; dark shading indicates convergence greater than 1×10^{-5} s^{-1}. The MSLP contour interval is 1 mb. The ordinate is longitude in degrees; the abscissa is latitude in degrees. The blank areas enclosed with a solid dark line indicate topography above 500 m. (From Arnup and Reeder 2007.)

- As discussed, the low-level convergence line that develops during the late afternoon/early evening on the western side of Cape York Peninsula is one of the most pronounced features of the Australian tropics. Sea-breeze circulations generate these lines almost daily when easterly winds prevail at low levels across the Peninsula. The relationship between these convergence lines and the initiation and organization of deep convection during the wet season is still unclear.
- At times cold fronts propagate equatorward as the anticyclone to their southwest expands across the continent. The reasons why cold fronts sometime propagate equatorward rather than eastward is yet to be determined. Moreover, recent work suggests that surges in the Australian monsoon may be closely related to equatorward propagating fronts (Berry and Reeder, 2015).
- Over the past half a century, the annually averaged, Australia-wide temperature, rainfall, and cloud cover have all increased, while the diurnal range has decreased. The increase in the Australia-wide summertime rainfall is largest over northwestern Australia where the trend may be as much as 60 mm per decade in some places. Significantly, this region of increased rainfall coincides with that of the northwestern Australian heat low. Although there has been recent work on the problem (Berry et al. 2011b, Ackerley et al. 2014, 2015), the relationship between the heat low, dry line and increased rainfall in the region remains to be determined.

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