Modelling the Subtropical Cold Fronts and Bores Observed During the Central Australian Fronts Experiment

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SUMMARY

High-resolution numerical simulations of two cold fronts are examined and compared with observations. The cold fronts modelled are the two main events from the Central Australian Fronts Experiment in 1991. The simulations are made using the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model with the initial and boundary conditions provided by analyses from the European Centre for Medium Range Weather Forecasts. The calculations agree well with the available observations, but because these data are still relatively sparse and the phenomena of interest are not sampled well spatially, the simulations provide a more complete picture of the fine-scale structure and evolution of the fronts than the observations alone. Both the model and the observations show that the fronts weaken rapidly during the late morning and afternoon when convective mixing in the boundary layer is most vigorous, but quickly re-develop overnight once the mixing ceases. In both cases the model reproduces the observed bore-like disturbance that develops during the early hours of the morning as the nocturnal inversion strengthens. In agreement with the observations, these disturbances propagate ahead of the cold front and develop a series of large-amplitude waves at their leading edge. In the second case the front encounters the cool air advected far inland by the sea breeze from the Gulf of Carpentaria, which assists in the development of a particularly prominent bore.

KEYWORDS: Bore  Cold Front  Morning Glory

1. INTRODUCTION

Except during the summer months (December to March), mid-latitude cold fronts in the Southern Hemisphere can extend far into the subtropics (Reeder and Smith 1998). These events are most common during the dry season and become less frequent as the continent warms and the mean subtropical ridge axis and mid-latitude westerlies migrate polewards. In the decade commencing 1988, a series of four field experiments were conducted in central and northern Australia to investigate the structure and behaviour of subtropical cold fronts and the bore-like disturbances they generate. The first, held in September 1988, was a small-scale pilot experiment in the Mount Isa region (Smith and Ridley 1990). (A map marking all the places mentioned in the text is shown in Fig. 1.) The Central Australian Fronts Experiment in 1991 (CAFE91) was the second of these and the results thereof were reported by Smith et al. (1995), Reeder et al. (1996), Menhofer et al. (1997a, b) and Deslandes et al. (1999). The third and fourth field experiments (CAFE96 and CAFE98) were held in a period during September-October in 1996 and 1998, respectively, and both were centred on the region around Alice Springs (Reeder et al. 2000; Preissler et al. 2002).

In total, fifteen fronts were documented in detail during the four field experiments and the principal findings were:

- The fronts are generally no deeper than about 1 km in the Australian subtropics, and they advance into a convectively well-mixed boundary layer, typically 3-4 km deep which, during the night, overlies a strong, shallow radiation inversion.
- Fronts in the subtropics rapidly weaken during the day as the mixing in the boundary layer intensifies, but quickly strengthen in the evening as the boundary layer turbulence weakens.
- As the daytime turbulent mixing increases the fronts tend to decelerate and often retreat.
- Of the 15 fronts observed during the field experiments, 13 crossed central Australia during the evening or early hours of the morning.
- As subtropical cold fronts approach the Gulf of Carpentaria they invariably generate bore-like disturbances in the evening or early hours of the morning. These bores often propagate ahead of the front on the strong surface-based nocturnal inversion that commonly forms in the region, or on the cool air advected inland by the sea breeze from the Gulf of Carpentaria. Over land, the bores generally dissipate before noon, by which time the stable layer is destroyed by convective mixing, but they decay much more slowly over the Gulf of Carpentaria.

Sometimes spectacular roll clouds, known in Australia as morning glories, are formed as moist low-level air is lifted and cooled adiabatically in the crest of the approaching bore wave (see e.g., Smith et al. 2006 and references therein). The morning glories generated over northern Queensland by subtropical cold fronts are often referred to as southerly morning glories because they move with a significant component from south to north, although Smith et al. (1986) used the term “southerly wind surges” as it emphasizes the sharp wind change that accompanies the disturbance and not all disturbances form cloud lines. More frequently, morning glory waves originate over Cape York Peninsula and propagate across the southern part of the Gulf of Carpentaria from the northeast. These so-called northeasterly morning glories form late in the evening or early hours of the morning as the east-coast and west-coast sea breezes meet over the peninsula (Clarke 1984, Noonan and Smith 1986, Smith and Noonan 1998, Goler and Reeder 2004, Thomsen and Smith 2006). Early reviews of the morning glory are those by Smith (1988) and Christie (1992), while a more recent review is given by Reeder and Smith (1998).

During October 2002 the Gulf Lines EXperiment (GLEX) was carried out by the Australian Bureau of Meteorology, Monash University and the University of Munich to study the dry season cloud lines that form in the Gulf of Carpentaria region of northern
Australia. As part of the experiment, observations were taken of northeasterly, southerly and southeasterly morning glories. Analyses of observations taken during GLEX are reported in Goler et al. (2006), Smith et al. (2006) and Weinzierl et al. (2007) and high-resolution simulations of two events are described by Thomsen and Smith (2006). The latter paper describes, inter alia, a simulation of a southerly wind surge associated with a cold front to the south. It was the success of this simulation and the insights that it provided that motivated the present study.

This paper examines similar numerical simulations of two subtropical cold fronts documented during CAFE91. Even with the additional observations from CAFE91, data over northern Australia are still relatively sparse and the phenomena of interest are not sampled well spatially. For this reason the strategy is to verify the simulations against the available observations and then to use the simulations to provide a more complete picture of the fine-scale structure and evolution of the fronts and bore-wave disturbances. All previous modelling work has been based on operational numerical weather prediction with horizontal resolutions no better than 50 km (Smith et al. 1995, Deslandes et al. 1999, Reeder et al. 2000; Preissler et al. 2002) compared with a resolution of 3 km in the present study.

The paper is structured as follows. Section 2 summarizes the numerical model and initial conditions. Sections 3 and 4 discuss the numerical simulations of the two cold fronts observed during CAFE91, comparing the simulations against the available observations. Some conclusions are drawn in Section 5.

2. The MM5 model

The MM5 model is described in detail by Grell et al. (1995). The model is non-hydrostatic and uses a finite difference approximation to the equations with $\sigma = (p - p_t)/(p_s - p_t)$ as the vertical coordinate, where $p$ is pressure, $p_s$ is the surface pressure and $p_t$ the top pressure, which is set to 100 mb. The present configuration is very similar to that used by Thomsen and Smith (2006). There are 23 $\sigma$-layers with 15 levels below 3 km. These are located at heights of approximately: 0, 40, 80, 150, 230, 300, 380, 540, 700, 870, 1200, 1550, 1900, 2300 and 2750 m, giving a relatively high resolution in the boundary layer.

The calculations are carried out on the two horizontal domains marked in Fig. 2. They comprise an outer domain with relatively coarse resolution and an inner domain with triple this resolution. The outer domain has $221 \times 221$ grid points with a horizontal resolution of 9 km and the inner domain has $361 \times 361$ points with a horizontal resolution of 3 km. The land use and orography are taken from the MM5 data set and have a 5’ resolution for the outer domain and 2’ resolution for the inner domain. The time step is 27 s for the outer domain and 9 s for the inner domain. The Grell cumulus parameterization scheme (Grell 1993) is implemented in the outer domain, but no cumulus scheme is used in the inner domain as the processes believed to be involved in the generation of morning glories are dry (e.g. Smith and Noonan, 1998). The MRF boundary-layer scheme as implemented in the National Centers for Environmental Prediction Medium Range Forecast system by Hong and Pan (1996) is selected for all domains. The Dudhia scheme (Dudhia 1989) is chosen to represent explicit moisture conversions. A short and long-wave cloud and ground radiation scheme that takes account of diurnal variations is used.

Analysis data from the European Centre for Medium Range Weather Forecasts (ECMWF) are used for the initial conditions and boundary conditions. These data have a horizontal resolution of 0.25°. An upper radiative condition is applied to reduce reflection of energy from the model top and prevent the build-up of numerical noise over the
orography. The MM5 model has a bucket soil moisture model. For this the soil moisture data from the Australian Bureau of Meteorology’s limited-area forecast model are used, as the ECMWF soil moisture scheme applies a lower limit which is much too moist for the north Australian dry season and has a deleterious effect on the generation of the sea breezes in the region. The initial conditions for the two cold fronts examined here are taken from the ECMWF analyses at 0000 UTC on 9 September 1991 and 16 September 1991; these fronts are referred to as Events 1 and 2, respectively. In each case the model is integrated forward for 48 h.

3. Event 1

(a) Synoptic environment for Event 1

The synoptic environment for Event 1 is illustrated in Fig. 2, which shows the ECMWF analyses of mean sea level pressure (MSLP) at 2200 EST 9 September (1200 UTC) and 1000 EST 10 September (0000 UTC). It shows also horizontal wind vectors and virtual potential temperature at 950 mb at these times. The cold front formed in the trough region between the two anticyclones relatively far from the center of the parent cyclone, which is the synoptic environment typical of almost all cold frontal passages across Australia (Reeder and Smith 1998).

At 2200 EST (1200 UTC) 9 September a trough lies across the continent from the northwest to the southeast. A strong ridge lies to the west of the trough, which is a characteristic feature of frontal passages in the region also. At low levels the wind is directed across the isobars towards the trough and the thermal ridge lies along the pressure trough with the highest temperatures in the northwest. Twelve hours later at 1000 EST (0000 UTC) 10 September the trough has progressed eastward accompanied by strong ridging from the west, and the northerlies inland from the Gulf of Carpentaria have strengthened (Fig. 2b). The thermal ridge continues to mark the trough and the warmest air remains in the northwest, but the air near the surface has cooled radiatively everywhere overnight.
Event 1 arrived at Mount Isa, which is close to the centre of both the observational network and the inner domain of the model, at about 0930 EST 10 September 1991. It weakened and stalled during the day and subsequently accelerated through Hughenden in the eastern most part of the network at about 2330 EST 10 September.

A time-series of the surface observations taken at Urandangi between 0500 EST and 1100 EST on 10 September is plotted in Fig. 3a. (Urandangi lies approximately 160 km southwest of Mount Isa and is marked on Fig. 1.) The singular feature of the time-series, and a signature common to subtropical cold fronts over Australia, is the double change. The first change at 0700 EST is marked by a pressure jump of 1.8 mb and a sharp change in wind direction from northwesterly to westerly. This change is followed by a series of pressure oscillations coinciding with fluctuations in the wind speed and direction. The observed wind and pressure signatures are typical of those associated with an internal undular bore. The second change at 0815 EST marks the air-mass boundary. At this boundary the pressure rises slightly, the wind backs from westerly to southerly, and the wind speed increases notably. Both the dew-point temperature and mixing ratio (not shown) fall sharply with the second change. The dashed lines in Fig. 3a show the corresponding curves taken from the model simulation. While the model does not capture the details of the undular bore, it does show a double line structure with a pressure jump and wind change (speed increase and direction change) at 0600 EST followed by a further freshening of the wind, a wind direction change and a pressure rise commencing at about 0715 and finishing at about 0830 EST. The second change brings about a steady fall in dewpoint temperature, but little change in temperature.

Figure 3b is similar to Fig. 3a, but for Burketown on the following morning. On this occasion, no bore-like disturbance was observed and none was predicted by the model. The model shows a steady backing of the winds from north-northwest at midnight to south-southeast at 0800 EST, similar to the observations except that the wind shift in the model is more gradual after 0315 EST. The observed and calculated dew-point temperature and pressure traces are in very good agreement.
Figure 4a shows a time-height section of potential temperature constructed from 6 hourly radiosonde ascents at Mount Isa around the time of passage there of Event 1. Time in this figure runs from right to left so that, to the extent that a Galilean transformation from time to space is appropriate, the section approximates a vertical cross-section through the front. Figure 4(b) shows the corresponding time-pseudo-height* section of potential temperature at approximately the location of Mount Isa constructed from the model simulation on the inner-grid.

The time-height cross-sections of observed and modelled potential temperature (Figs. 4a and 4b) shows that the model captures the key features in the observations. In the early hours of the morning on 10 September, a shallow radiation inversion forms beneath a weakly stable remnant of the mixed layer from the previous day. Above this is the more stable free atmosphere. Throughout the early hours of the morning the stable layer deepens until shortly after 0800 EST when the mixed layer begins growing. Although the front arrives at 0930 EST, its passage is obscured by the daytime heating and associated mixing which opposes the local cooling from the advection of cold air behind the front. The airmass change becomes apparent only after the diabatic heating and mixing begins to wane in the late afternoon. Recently Reeder and Tory (2005) investigated the effects of diabatic heating and cooling on frontogenesis in an idealized numerical model and found that the cross-front potential temperature gradient is weakened principally by the differential heating produced in the depth of the mixed layer.

(c) Modelled structure and evolution of Event 1

Having established that the model simulation is in reasonable agreement with the observations, it can be used to deduce the structure and evolution of Event 1 as it traversed northern Queensland. The analysis begins with the early evolution on the 9 km domain outlined in Fig. 2. Figure 5 shows plots of virtual potential temperature, horizontal wind vectors and isobars of MSLP at three hour intervals commencing 1500 EST, 9 September. At 1500 EST there is a prominent heat trough oriented northwest to southeast and marked in the figure. This heat trough is part of the heat low over Western Australia (see Fig. 2a). On the northern flank of the heat trough the flow is northwesterly and on the southern side it is westerly. Three hours later (panel b) a band of enhanced convergence (larger in magnitude than $1 \times 10^{-4}$) has formed along the axis of the heat trough. At 2100 EST strong southwesterlies have developed on the southwestern side of the trough. These are associated with the ridging across the continent and the northward progression of the cooler air which is now evident in the southwestern corner of the figure. In the first three panels, the heat trough axis and the band of convergence within it remain approximately stationary.

At midnight (panel d) the band of convergence associated with the heat trough and that associated with the midlatitude cold front have merged and subsequently, as shown below, they move northeastwards as a single cold front. A significant feature at this time is that the largest temperature gradients are found immediately to the southwest of the wind change poleward of 23°S while north of this latitude there is an increasing separation between the wind change and the region of largest temperature gradient. It is evident that the convergence line is coincident with the wind change. Note also the development

* Pseudo-height is a pressure dependent height-like coordinate defined by $z = (c_p \theta_0 / g) [1 - ((p_t + \sigma(p_s - p_t))/p_0)^R / c_p]$], which is identical with geometrical height in a neutrally stratified atmosphere. Here, $\sigma = (p - p_t)/(p_s - p_t)$ is the vertical coordinate used in MM5, $p$ is the pressure, $p_s$ is the surface pressure, $p_t$ the top pressure, which is set to 100 mb, $g$ is the acceleration due to gravity, $R$ is the gas specific constant for dry air, $c_p$ is the specific heat for dry air, and $\theta_0 = 273.15$ K and $p_0 = 1000$ mb are constant reference values of potential temperature and pressure.
of convergence lines corresponding to the sea breezes over Cape York Peninsula and the onshore advection of cooler air over the peninsula and around the gulf.

Figure 6 shows the virtual potential temperature and horizontal wind vectors on the $\sigma = 0.955$ surface, and the regions of horizontal convergence larger in magnitude than $1 \times 10^{-4}$ on the $\sigma = 0.9975$ surface. Six times are plotted: 2100 EST 9 September, 0300 EST 10 September, 0900 EST 10 September, 1500 EST 10 September, 2100 EST 10 September and 0300 EST 11 September. The two key features of convergence field depicted in panel a (2100 EST 9 September) are: the sea-breeze boundary which, at this time, is located 150 km inland from the gulf coast; and the heat trough in the southwestern corner of the domain (see Fig. 5c). The wind on the gulf side of the sea breeze boundary is directed perpendicular to the boundary and away from the gulf. To the south of the trough the wind is strong and southerly, while on the northern side the wind is strong and northerly or northwesterly. At 3 km resolution, the pattern of convergence in the trough comprises a series of short lines.

As shown in Fig. 5d, the convergence line within the heat trough merges with a midlatitude cold front at about midnight, after which the two lines move northeastswards as a single subtropical cold front. Panel b of Fig. 6 shows that at 0300 EST 10 September the convergence line is more coherent than it was six hours earlier, but is made up of many individual segments. In the southeastern portion of the line, the maximum temperature gradient lies just to the rear of the convergence line, but it lags further behind in the northwest. In the northeastern part of the domain, inland from the Gulf of Carpentaria, a series of convergence lines mark a northeasterly morning glory, which has propagated southwestward from the middle part of the Cape York Peninsula where it was generated.
The sea-breeze circulation is not confined to the coastal margin, but propagates several hundred kilometers inland after sunset. This circulation strengthens and the sea-breeze front accelerates inland as the turbulent day-time boundary layer changes to stable night-time conditions. This is consistent with work of Physick and Smith (1985) who found that sea breezes in northern Australia continue to propagate far inland well after sunset.

Panel c (0900 EST 10 September) is close to the time that the disturbance reached Mount Isa. Now, two curved convergence lines, again broken along their lengths, lie across the inner model domain extending from about 20° S in the western part to the southeastern corner. The wind ahead of the leading line is northwesterly, but backs, becoming westerly on the southern side. The wind backs sharply again across the second line, which is followed by strong southerlies. By this time, the convergence lines lie parallel to the isentropes on their southwestern side and the second line marks the arrival of the cooler air.

This double wind change from northwesterly to westerly to southerly is very similar to that recorded in the time series from Urandangi (Fig. 3). The northeasterly morning glory arrived at Burketown at 0956 EST on 10 September (Menhofer et al. 1997), which means that the simulated northeasterly morning glory disturbance depicted in Fig. 6a is a little too fast. At the leading edge of the observed morning glory the pressure rose by 0.5 mb (Menhofer et al. 1997) whereas the model produces a surface pressure jump of approximately 1 mb.
At 1500 EST 10 September (panel d) a convergence line to the south of the Gulf coast marks the afternoon sea breeze front, on the northern side of which is a strong temperature gradient. The convergence line running southeast from about 19°S 139°E marks the subtropical cold front. There are strong southeasterly winds to the southwest of this line, but the temperature gradients in the cold air have weakened since 0900 EST.

By 2100 EST 10 September (panel e) the convergence marking the subtropical cold front has increased and the part between 137° and 140° has collided with the sea breeze. Subsequently, at 0300 EST 11 September (panel f), the model produces a convergence line indicative of a southerly morning glory during the early hours of the morning as the front encounters the cool air advected inland by the sea breeze. This line is curved and lies approximately east-west in the northernmost part of the model domain. To the south lies the convergence line marking the remnants of the subtropical cold front and further south again a convergence line that, in animations of the fields, can be traced back to the sea breeze. While on this day no southerly morning glory was observed at Burketown, the surface wind trace there showed a gradual change from north-west to south-west commencing around 0400 EST. Unfortunately, no satellite imagery were available for this day.

Figure 7 shows the meridional-height section of virtual potential temperature at the times corresponding Fig. 6. The longitude of the section is chosen to be 138° E, which is close to that of Urundangi. In Fig. 7 the coastline is located 110 km from the northern boundary of the domain. At 2100 EST 9 September (panel a), the leading edge of the sea breeze is located 160 km inland. The cool air is only a few hundred metres deep near the leading edge, but increases in depth to nearly 1.5 km at the northern boundary of the domain. There is a pronounced thermally-direct circulation at the leading edge with a northerly component to the low-level flow across virtually the whole domain. Above about 2 km the flow has a southerly component. By 0200 EST 10 September (panel b) a combination of radiative cooling and onshore advection by the sea breeze results in a shallow layer of cool air across the entire domain. As the potential temperature gradient weakens, so does the vertical circulation.

Daytime radiative heating and the attendant vigorous mixing results in a deep mixed layer over most of land (panel d; 1500 EST 10 September). The mixing produces a continental airmass that is relatively homogeneous in the horizontal, with the cooler gulf air and post-frontal air confined to the northern and southern parts of the cross-section respectively. After sunset, as the mixing ceases, both the post-frontal air and the gulf air surge towards the centre of the domain (panel e; 2100 EST 10 September). During the early hours of the morning, as the nocturnal inversion strengthens and the front encounters the cool air advected far inland by the sea breeze, the model produces a low-level wave-like structure, which propagates ahead of the airmass change (panel f; 0300 EST 11 September).

(d) Nocturnal frontogenesis and bore formation

The material rate of change of the magnitude of the horizontal potential temperature gradient $|\nabla_h \theta|$ is known as the frontogenesis function, and was introduced by Petterssen (1936) as a measure of the tendency of the atmosphere to develop fronts (see also the generalization by Keyser et al. 1988). On the sphere, the frontogenesis function can be expressed as

$$\frac{D}{Dt} |\nabla_h \theta| = -\frac{1}{2} |\nabla_h \theta| (D - E' \cos(2\beta)) - \frac{\partial \theta}{\partial \sigma} \mathbf{n} \cdot \nabla_h \dot{\theta} + \mathbf{n} \cdot \nabla_h \dot{Q} \quad (1)$$
Figure 6. Event 1. Virtual potential temperature (dashed contours) and horizontal wind vectors on the $\sigma = 0.955$ surface at (a) 2100 EST 9 September, (b) 0300 EST, (c) 0900 EST, (d) 1500 EST, (e) 2100 EST 10 September and (f) 0300 EST 11 September 1991. Shown also are the regions of horizontal convergence larger in magnitude than $1.5 \times 10^{-4} \text{ s}^{-1}$ on the $\sigma = 0.9975$ surface.

where $\theta$ is the potential temperature, $\dot{Q}$ is the diabatic heating rate, and $n = \nabla_h \theta / |\nabla_h \theta|$ is the unit vector pointing along the potential temperature gradient towards colder air. In addition, $D = \partial u / \partial x + (\cos \varphi) \partial (v / \cos \varphi) / \partial y$ is the horizontal divergence, $E = \partial u / \partial x - (\cos \varphi) \partial (v / \cos \varphi) / \partial y$ is the stretching deformation, $F = \partial v / \partial x + (\cos \varphi) \partial (u / \cos \varphi) / \partial y$ is the shearing deformation, $E' = \sqrt{E^2 + F^2}$ is the total deformation, $\varphi$ is the latitude, $x$ is the arclength along a line of constant latitude, $y$ is the arclength along a line of constant longitude, $\alpha = \tan^{-1} ((\partial \theta / \partial x) / (\partial \theta / \partial y))$, $\delta = \frac{1}{2} \tan^{-1} (E / F)$ is the angle between the $x$ axis and the axis of dilatation, and $\beta = \delta - \alpha$ is the angle between the axis of dilatation and the isentropes.

Physically, the first term on the right hand side of Eq. 1 describes the contribu-
Figure 7. Event 1. Meridional-height section of virtual potential temperature along 138° E at (a) 2100 EST 9 September, (b) 0300 EST, (c) 0900 EST, (d) 1500 EST, (e) 2100 EST 10 September and (f) 0300 EST 11 September 1991. Vectors represent circulation in the plane of the cross section. Shown also are the regions of horizontal convergence larger in magnitude than 1.5 \times 10^{-4} \text{ s}^{-1}. Dashed contours represent negative, solid lines represent positive values.
tion to material rate-of-change of the horizontal potential temperature gradient from the combined effects of convergence and deformation. The second term represents the contribution due to the tilting of vertical gradients of potential temperature into the horizontal, while the third term is the contribution from differential diabatic heating.

The first term on the right hand side of Eq. 1 at 0300 EST, 0900 EST and 1500 EST 10 September is plotted in Fig. 8. The fields show a great deal of spatial variability as the pattern of orography is imprinted strongly on the low-level winds and potential temperatures, and the calculation of the frontogenesis function involves products of differential quantities.

Marked also in Fig. 8 are those regions where the convergence exceeds $10^{-4} \, \text{s}^{-1}$ in magnitude. During the early hours of the morning (panel a) the subtropical front lies in the southwestern part of the model domain (see Fig. 6b). At this time the horizontal wind field acts to intensify the front, although there are regions of pronounced local contributions to frontolysis. By 0900 EST (panel b) there are strong, relatively well-organized contributions to frontogenesis along the whole subtropical front. The north-easterly morning glory, which lies in the northeastern part of the domain, is marked by bands of frontogenesis and frontolysis. During the mid afternoon (panel c), the contributions to frontogenesis along the subtropical front is much weaker, and the main region of frontogenesis lies inland from the gulf coast, marking the leading edge of the sea breeze. There are pronounced contributions to frontolysis behind the sea breeze front.

The tilting and diabatic contributions to Eq. 1 are not shown. The tilting term is especially noisy as it appears to be linked more closely to the variations in the orography than to larger-scale organized circulations forced by the subtropical front. Although the diabatic contribution to the frontogenesis function is undoubtedly important, it is ignored in these calculations as diabatic heating rate is not saved by MM5. Nonetheless, diabatic processes affect the evolution of the flow, thereby indirectly affecting all terms in the frontogenesis function. The frontogenesis function in the neighbourhood of the front is weakly positive during the afternoon, even though Fig. 6 shows that the temperature gradients associated with front weaken at this time. Presumably, during the afternoon the direct frontolytical effect of heating overwhelms the weak adiabatic contribution to frontogenesis. This result is consistent with Deslandes et al. (1998) who examined aspects of Event 1 using the Australian Bureau of Meteorology’s Regional ASsimulation and Prognosis system (RASP), which had a horizontal resolution of 150 km. The results are consistent also with those of Reeder and Tory (2005) who found that differential heating produced by horizontal variations in the mixed-layer depth was frontolytic during the day.

Fronts are commonly interpreted locally as steady gravity currents (see Smith and Reeder 1988 and references therein). A feature of a steady gravity current is the advection of denser fluid towards the head, in which case the low-level flow behind the leading edge $U$ exceeds its translation speed $c$. In contrast, the low-level flow behind a steadily propagating bore is less than the translation speed, so that $U - c < 0$. Recently, Thomsen and Smith (2006) used this criterion to examine the evolution of the east coast sea breeze over Cape York Peninsula into a propagating bore-like disturbance corresponding with a northeasterly morning glory. They applied the same criterion to demonstrate the evolution of a subtropical cold front into a bore-like disturbance corresponding with a southerly morning glory. However, it is known that under certain circumstances, cold fronts may propagate also in the sense that $U - c < 0$ (e.g. Reeder and Smith, 1986, 1987, 1988, Smith and Reeder 1988). Smith and Reeder (1988) showed that, in the absence of an along-front temperature gradient, the front can be maintained only by confluence of the warm and cold air by motions in a vertical plane normal to the surface front. Their result
Figure 8.
Event 1. Contribution to the frontogenesis function from convergence and deformation on the $\sigma = 0.9$ surface at (a) 0300 EST, (b) 0900 EST and (c) 1500 EST 10 September 1991. Regions where the magnitude of the frontogenesis function exceeds $5 \times 10^{-9}$ K m$^{-1}$ s$^{-1}$ are shaded. Light grey are negative (frontolysis) and dark grey are positive (frontogenesis). Regions in which the horizontal convergence exceeds $10^{-4}$ s$^{-1}$ are contoured.
implies the relative advection of cold air toward the frontal zone, implying $U - c > 0$. As frontogenesis proceeds and the front collapses to near discontinuity, the along-front temperature gradient becomes negligible compared with the cross-front gradient and it follows that $U - c$ becomes small or positive. Smith and Reeder noted that $U - c > 0$ does not necessarily indicate that the front has the character of a gravity current. Moreover, as the condition $U - c < 0$ does not necessarily indicate that the front has the character of a bore, it would appear that an examination of the sign of the front-relative flow in isolation is ambiguous for determining the transformation of a front into a bore. However, we would argue that the dual criteria of a changing in $U - c$ from positive to negative in conjunction with frontogenesis is indicative of such a transformation.

The possible transformation of the subtropical front in Event 1 into a bore is examined in Fig. 9, which shows contours of $U - c$. At 2200 EST 10 September, $U - c$ is positive to the south of the front. This means that the flow in the direction of the disturbance is faster than the disturbance itself and it implies that cooling brought about by the passage of the disturbance is produced principally by the advection of cold air from the southwest. Four hours later (panel b), the distribution of $U - c$ is dramatically different. The relative flow is almost everywhere negative, which means that the disturbance moves faster than the wind in the direction of translation. This is one of the characteristics of a bore, and it implies that any cooling must be produced principally as air parcels are lifted and adiabatically cooled at the leading edge of the disturbance. Thus, the change in sign of $U - c$ signals a fundamental change in the dynamics of the disturbance.

4. Event 2

(a) Synoptic environment for Event 2

The ECMWF analyses at 1000 EST (0000 UTC) and 2200 EST (1200 UTC) 16 September 1991 are shown in Fig. 10. The synoptic environment is very similar to Event 1 (Fig. 2), the key features being the trough across the northeastern part of the continent, and the strong ridge and warm air to the northwest. Comparing Figs. 2 and 10 shows that even the positions of these synoptic features are very similar. However, the cold front in Event 2 passed through Mount Isa just after midnight, at about 0020 EST 17 September 1991 (1420 UTC 16 September), whereas that in Event 1 reached Mount Isa at 0930 EST 10 September 1991 (2330 UTC 9 September). Consequently, the key difference between the two events is that the latter passed quickly through the observational network towards the gulf in the late evening and early hours of the morning, whereas the former reached Mount Isa mid-morning, weakened and decelerated, and finally reached the gulf in the early hours of the following morning.

(b) Comparison between the observations and simulation of Event 2

Figure 11 shows time-height sections of potential temperature from the radiosonde ascents made at Mount Isa and from the corresponding model profiles. An intense, but shallow radiation inversion is observed to form beneath a deep well mixed-layer prior to the arrival of the front. The model simulation produces the same features, although they are weaker and more diffuse. In the model, a strong updraught accompanies the leading edge of the change. Both the observed and modelled front are shallow, no more than 1.5 km deep, although the model does not reproduce the sharp inversion capping the cold air. The coldest air arrives at Mount Isa at about 0900 EST, after which time the
potential temperature increases during the day as the warming associated with diabatic heating exceeds the cooling produced by the post-frontal advection of cold air. The model captures this effect also, but produces the lowest potential temperature at 0600 EST.

(c) Modelled structure and evolution of Event 2

Figures 12 and 13 show the modelled divergence and horizontal wind on the $\sigma = 0.995$ surface, and meridional-height sections of equivalent potential temperature along 140°E at three times: 0000 EST 17 September 1991, 0600 EST 17 September and 1000 EST 17 September. At midnight (Figs. 12a and 13a) the sea breeze is located far inland and is approaching the cold front. In the early hours of the morning (Figs. 12b and 13b), the cold front meets the decaying sea breeze circulation from the Gulf of Carpentaria and develops a pronounced potential temperature jump at its leading edge. Subsequently, a bore-wave disturbance, indicative of a southerly morning glory, propagates ahead of cold air (Figs.
Figure 10. Event 2. ECMWF analyses at (a) 1000 EST (0000 UTC) 16 September and (b) 2200 EST (1200 UTC) 16 September 1991. MSLP (dashed lines), horizontal wind vectors and virtual potential temperature (shaded) at 850 mb. Contour intervals are 2 mb and 3 K. The two boxes centred over northeastern Australia show the outer and inner domains used in the simulations with MM5.

Figure 11. Event 2. (a) Time-height section of potential temperature from radiosonde ascents at Mount Isa. Time increases from right to left along the abscissa. The height in km is plotted along the ordinate. Contour interval is 2 K. (Reproduced from Smith et al. 1995.) (b) Time-height section of potential temperature from the model. Contour interval is 2 K. Pseudo-height in km is plotted along the ordinate.

12c and 13c) and reaches the southern gulf coast around 0900 EST. Observations taken during CAFE91 show that a southerly morning glory did reach Burketown, located on the southeastern coastline of the Gulf of Carpentaria, at 0638 EST 17 September. It was observed to propagate at 15.3 m s$^{-1}$ from a direction of 205$^\circ$ and was marked by a pressure jump of 1.4 mb. The pressure jump in the model is approximately 1 mb.
Figure 12. Event 2. Virtual potential temperature (dashed contours) and horizontal wind vectors on the $\sigma = 0.955$ surface at (a) 0000 EST, (b) 0600 EST and (c) 1000 EST 17 September. Shown also are the regions of horizontal convergence larger in magnitude than $1.5 \times 10^{-4}$ s$^{-1}$ on the $\sigma = 0.9975$ surface.

The model shows that between 0600 and 1000 EST 17 September the relative flow (Fig. 14) changes dramatically. Behind the leading edge of the subtropical front at 0600 EST, the flow in the direction of the disturbance is almost everywhere slower than the disturbance itself. In contrast, there are only small regions of positive relative flow at 1000 EST, which is consistent with the interpretation that the leading disturbance is transformed into a bore.

5. Conclusions

Numerical simulations of two subtropical cold fronts have been compared with observations taken during CAFE91, a field measurement campaign focussed on northern and central Queensland in the late dry season of 1991. These simulations have been used to investigate the fine-scale structure and evolution of these fronts and the generation of northward propagating bores known as southerly morning glories.

The numerical calculations agreed well with the observations made during CAFE91. Consistent with earlier studies, both the model and the observations showed that the strength of the fronts changes markedly from day to night. The fronts weaken during the late morning and afternoon when convective mixing in the boundary layer is most vigorous, but quickly re-develop overnight as the mixing subsides.

In both cases examined, the model produced regions of negative relative flow in the early hours of the morning as the nocturnal inversion strengthened, following a period of rapid frontogenesis, and was interpreted as the formation of a bore at the leading edge of the front. In contrast the model generated large regions of positive relative flow towards
the front following periods of frontolysis. In Event 1 the bore formed both in model and observations before the front interacted with the sea breeze from the gulf coast. We are unaware of other documented cases where this is the case.

The main difference between Events 1 and 2 was that former passed through Mount Isa mid-morning whereas the latter passed through shortly after midnight. Consequently Event 2 encountered the cool air advected far inland by the sea breeze from the Gulf of Carpentaria, which produced a particularly large-amplitude bore. In agreement with the observations, the bore propagated ahead of the front, developing a series of large-amplitude waves at its leading edge. Observations taken during CAFE91 and other field experiments indicate that during the dry season, subtropical cold fronts almost always generate internal bore waves in the early hours of the morning.

Acknowledgements

We are grateful to the ECMWF for providing analysis data. The first author gratefully acknowledges receipt of a research scholarship from the University of Munich, which
supported this study, as well as a Rupert Ford Travel Award from the Royal Meteorological Society, which enabled him to visit research facilities in Australia, where part of this work was carried out.

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