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Southerly nocturnal bores over northeastern Australia

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Analyses of one-minute data from the Automatic Weather Stations (AWSs) in the Gulf of Carpentaria region are used to study southerly nocturnal bores over northeastern Australia. The data cover the time period 1 August to 31 December in the three years 2012-2014. A total of twelve days on which a bore passed over the region of interest were found. Ten of the disturbances occurred between August and mid-October in the presence of synoptic-scale ridging across the continent behind a frontal trough. The other two occurred in early November in the presence of localized ridging behind an inland trough separate from a frontal trough. Six of the bores were followed some hours later by a clear air mass change. Four of the twelve cases are examined in detail wherein interpretations of the AWS data are aided by analysis fields from European Centre for Medium range Weather Forecasts (ECMWF). It is found that the ECMWF analyses are able to capture the troughs as well as the timing of their passage through the AWS network. However, the horizontal resolution of these analyses is inadequate to capture the generation of the bores.

Key Words: cold fronts; undular bores; Morning Glory; inland trough

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1. Introduction

In the late dry season of 1979, a field experiment was organized in the Gulf of Carpentaria region of northern Australia to study the "Morning Glory" phenomenon (Smith and Goodfield 1981, Clarke *et al.* 1981). Morning Glory is the name given to an often spectacular low-cloud formation that occurs frequently over the southern part of the gulf at certain times of the year, principally in the late dry season September to mid-November. The clouds are now known to be a type of wave cloud that forms in the crests of undular bore-like wave disturbances. The majority of these disturbances are generated in the evening over Cape York Peninsula and move southwestwards during the night and early morning. A recent review of the Morning Glory and related phenomena is given by Smith and Reeder (2014).

It came as a total surprise at the end of the 1979 field experiment to observe a similar type of cloud line at Burketown moving from the south. A year later, two similar southerly disturbances were documented and following further field experiments it became apparent that such occurrences were not uncommon (Smith *et al.* 1982, 1986). However, during the early years, the origin of these disturbances was a mystery.

A summary of the early southerly morning glories documented was presented by Smith *et al.* (1986), whose analyses of available data for the events pointed to a possible connection with cold fronts crossing the continent to the south, at least in some cases, 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, a situation that motivated an observational programme to obtain the necessary data.

A pilot experiment was organized in September 1988 to document one or two cases of low-latitude cold fronts (Smith and Ridley 1990) and two subsequent experiments, more extensive in scope, were carried out in the early and mid-90's. During the first of these, the Central Australian Cold Fronts experiment (CAFE) in 1991, three fronts were documented and an unprecedented data set was obtained for a cold front on 10 September that crossed the northern part of the continent and transformed over night into a southerly Morning Glory (Smith et al. 1995). Surface data showed that the bore became separated from and moved ahead of the cold front over central Australia. As far as we are aware, this was the first documentation of an event of this kind.

In September 2002, a major field experiment (the Gulf Lines EXperiment, GLEX) was organized to study another kind of cloud line that is common over the Gulf of Carpentaria, the so-called North Australian cloud line, or simply gulf line (Drosdowsky and Holland 1987, Drosdowsky *et al.* 1989, Goler *et al.* 2006). In the dry season, this is typically a line of congestus clouds that stretches across much of the gulf and moves westwards with time. On two days during this experiment, two particularly interesting southerly Morning Glory disturbances were documented as well (Smith *et al.* 2006).

A special feature of the first event, on 29 September, was a 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 dryline. As in many earlier events documented, the bore and air mass change were accompanied by ridging over the northeastern part of the continent. In this particular 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 out over the gulf. At Karumba, there were strong southeasterly winds with blowing dust following the change.

In the second event, on 9 October, 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. The synoptic situation was very similar to that for the first event, namely a ridge of high pressure moving across the continent and the inland trough line on its northeastern side moving northeastwards towards the gulf. Recognition of this favourable pattern, which emerged from the earlier studies of Smith *et al.* (1982, 1986), enabled the event to be forecast 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 optimally deploy the instrumented research aircraft available to the experiment.

In 2005, through an initiative of the then Director of the Northern Territory Regional Office, G. Garden, the Bureau of Meteorology began to install data loggers on their Automatic Weather Stations (AWSs) in the Territory. This initiative was later followed by the Queensland Regional Office so that there is now a network of such stations across northern Australia recording near-surface data every minute.

In a first attempt to construct a climatology of all types of Morning Glory disturbances, Nudelman *et al.* (2010) analysed the available data from the AWS network in 2006. In their study of pressure jumps around the Gulf of Carpentaria region, they identified five disturbances having a southerly component of motion during the period August to November. A common feature of four of the disturbances was the ridging overnight across central Australia with a pronounced trough to the north of the ridge that was displaced further northwards. This situation is common to many of the southerly events so far documented (Smith *et al.* 1982, 1986, 1995, 2006; Thomsen and Smith 2006) and increases support for the mechanisms of formation analysed in detail by Thomsen and Smith (2006), Weinzierl *et al.* (2007) and Thomsen *et al.* (2009). The exception was one event, where, although there was an inland trough analysed to the south of the Gulf, the ridging was confined to the south of the continent. Events such as this had been documented previously in the literature (Smith *et al.* 1982, 1986) and a similar case is examined later in this paper.

Since the Nudelman *et al.* study, the number of AWS stations in the gulf region fitted with data loggers has increased and there is now an approximate meriodional line of five stations from Urandangi (138.31°E, 21.61°S) to Mornington Island (139.4°E, 16.55°S). The stations near this line are particularly suitable for investigating the generation and evolution of southerly bore-like disturbances of the type documented in the CAFE and GLEX experiments, in which the disturbances were generated by cold fronts. The availability of the high temporal resolution AWS data coincides with the recent availability of analysis data from the ECMWF with a moderately high spatial distribution (0.125 deg. in latitude and longitude). These analyses have the potential to provide a useful mesoscale setting for investigating the generation of southerly bores.

The present paper seeks to utilize these two new data sources in a further analysis of southerly nocturnal bores, including their frequency of occurrence. Case studies of selected bore disturbances will be presented using more complete data than were available of most previous southerly events. The paper seeks also to determine the ability of the ECMWF analyses to capture shallow cold frontal troughs and bores over northeastern Australia.

The paper is organized as follows. Section 2 presents a climatology of southerly bore events during the period August to December in each of the years 2012 to 2014. Case studies of four events are described in Section 3 and an overview of all other events that occurred during the entire period of investigation is presented in Section 4. A summary and conclusions are given in Section 5.

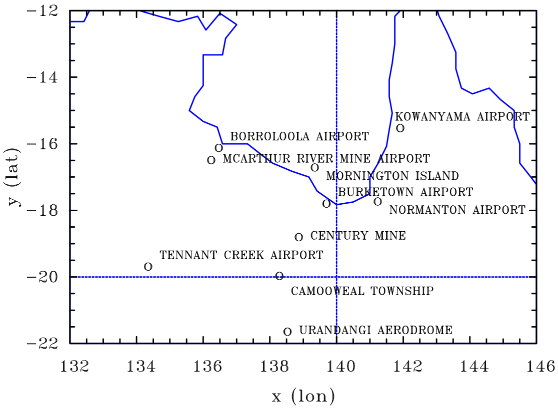

Figure 1. Map of the Gulf of Carpentaria region showing the locations of Bureau of Meteorology automatic weather stations from which data were analysed.

2. Southerly bore climatology

One-minute data from Bureau of Meteorology AWSs south of the Gulf of Carpentaria are analysed for the period

Table I. Times of passage of southerly bores (denoted B), fronts (denoted F), dry lines (denoted D) and other disturbances (denoted O) during the period of 1 August to 31 December in each of the years 2012 to 2014. Times where a disturbance passes over a station are given in EST. A bore refers to a pressure jump with or without following undulations in pressure when there is no appreciable temperature change other than that produced by downward mixing of potentially warm and dry air from aloft by turbulence at the bore. A front refers to an airmass change in which there is a sustained fall in temperature and a change in dew point temperature. A dry line passage refers to a sustained change in the dew point temperature without a marked change in temperature, or even with a surface temperature rise after sunrise. O refers to significant wind change without a signature in temperature or dew point temperature, or where pressure data are missing (one case at Urandangi).

Date	Urandangi	Camooweal	Century Mine	Burketown	Mornington Island
30 Aug 2012	no data	B 0700			
28-29 Sep 2012	F 2215	B 0230 / F 0300	B 0500 / F 0830	B 0630 / D 1900	
06 Nov 2012	O 0400	B 0700 /O 1000			
07 Nov 2012	O 2330 (06 Nov)	B 0300			
17 Aug 2013	B 0430 / F 0500 / D 0730	B 0815			
26 Sep 2013	B 0700 / D 0930				
11 Oct 2013	B 0145 / F 0200	B 0430 / D 0800	B 0700		
13-14 Oct 2013	F 1430	F 1800	B 2200 / D 2300	B 0100 / D 0400	B 0315 / D 0745
01 Aug 2014	B 1000				
02 Sep 2014	B 0200	B 0530			
09-10 Sep 2014	B 2330	B 0500			
24 Sep 2014	B 0630	B 1100			

from 1 August to 31 December in each of the years 2012 to 2014. The AWS network in this region is depicted in Figure 1. The climatology is focussed on time-series of relevant meteorological parameters at the locations Urandangi, Camooweal, Century Mine, Burketown and Mornington Island, which form an approximate line from South to North between 138°E to 140°E. In the case studies presented in the next section, we investigated data also from the other AWS stations shown in Figure 1.

In the entire time period, a total of twelve days were identified on which a southerly bore passed at least one of the five AWS stations from Urandangi to Mornington Island. These southerly bore events are equally distributed over the three years of inspection, i.e. four southerly bore events per year. The average number of four events per year matches the results from the observational study by Nudelman *et al.* (2010). From the same AWS network they analysed five disturbances approaching from the south during the period August to November 2006.

Most of the southerly bores in the years 2012-2014 occurred during August (3 events) and September (5 events). Two events occurred during October, two during November and no events were identified during December. The times of passage of the southerly bores at each of the five stations between Urandangi and Mornington Island are summarized in Table I. Times are given in Australian Eastern Standard Time (henceforth abbreviated EST). As the table shows, only one southerly bore event (that of 13-14 October 2013) could be detected all the way from Urandangi to Mornington Island. In the event of 28-29 September 2012, the bore reached as far as Burketown. In most other cases the bore could not be detected at stations north of Camooweal.

Five of the bores were followed some hours later by a clear air mass change where the wind direction changed to a southerly. The passage times of these disturbances are included in the table also. In some cases, the air mass change had characteristics of a cold front (denoted by the letter 'F') with an abrupt decline in temperature. In other cases, the air mass change has the form of a dry line characterized mainly by a fall in dew point temperature (denoted by the letter 'D'). A significant wind change without a signature in temperature or dew point temperature, or where pressure data are missing are denoted by the letter "O".

3. Case studies

Since southerly bores are a phenomenon confined to the lower atmosphere, the large-scale environment that is conducive to their genesis can be described adequately by the mean sea level pressure (MSLP) analyses. Apart from two exceptions (6 and 7 November 2012), the particular synoptic situation during the southerly bore events summarized in Table I reveal common features: an inland trough that is displaced further to the northeast followed by ridging across the continent. In the following sections, four cases of southerly disturbances are analyzed in detail: the first two events are characterized by the typical synoptic conditions mentioned above, but show certain differences that are worth highlighting; the third and fourth events to be discussed occurred on 6 and 7 November 2012 where, in contrast to the other cases, the synoptic situation is not characterized by ridging across the continent.

3.1. *Event of 17 August 2013*

Figure 2 shows the synoptic situation for the Australian region at 1200 UTC 16 August 2013 and twelve hours later on the basis of Bureau of Meteorology MSLP analyses. An approximately northwest-southeast oriented trough line lies across central Australia separating two broad high pressure systems, one centred over the Indian Ocean and the other east of the Australian continent. At 1200 UTC (2200 EST), the trough line is located a little southwest of Urandangi (138.31°E, 21.61°S). Twelve hours later, the trough line has moved northeastwards, but is not analysed north of about 20°S. The movement of the trough is accompanied by ridging over central Australia. The ridging overnight behind a trough that moves towards the northeast is a common feature in most of the cases summarized in Table I and,

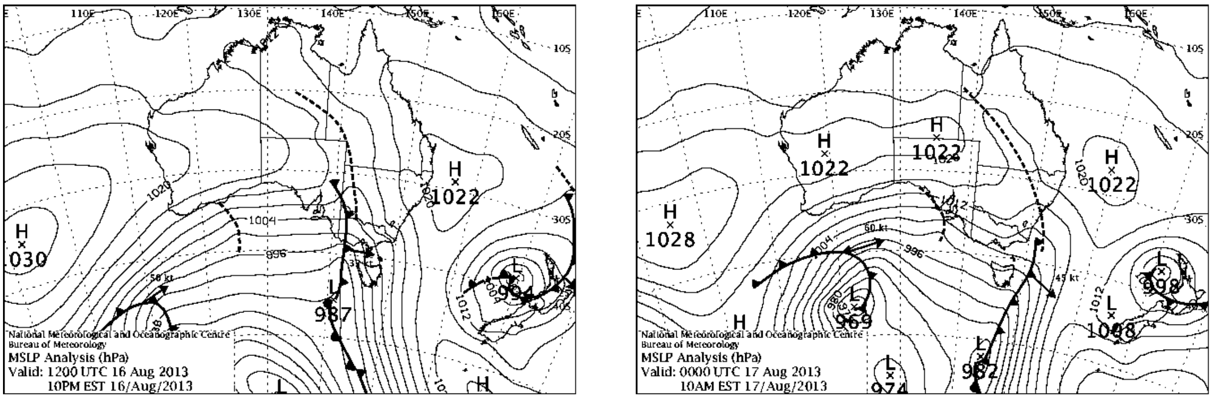

Figure 2. Bureau of Meteorology mean sea level isobaric analyses for the Australian region at 1200 UTC on 16 August (left) and 0000 UTC on 17 August 2013 (right).

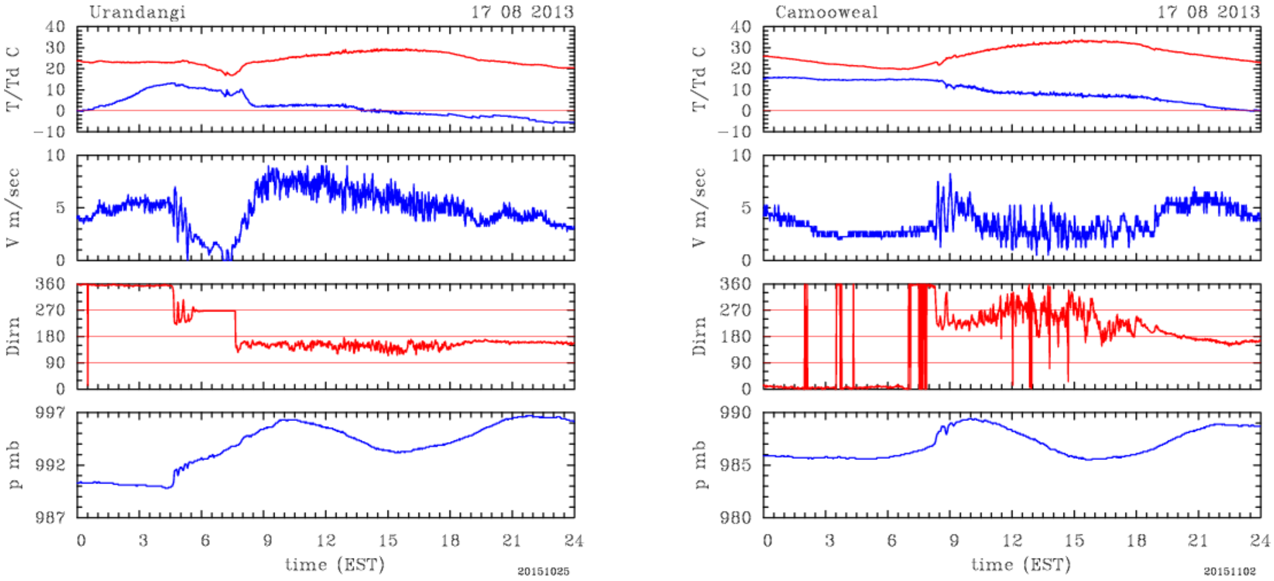

Figure 3. Time-series of temperature (T), dew point temperature (T_d), wind speed (V) and direction ($Dirn$), and pressure (p) observed by Bureau of Meteorology automatic weather stations at Urandangi (left) and Camooweal (right) on 17 August 2013.

as shown in previous studies (e.g. Smith *et al.* 1995), the trough line, itself, marks the leading edge of a shallow cold front. Differences lie in the strength and northward extent of the ridging over the continent and thus in the distance over which the trough line is pushed northwards. In most cases, exemplified by the event of 17 August 2013, southerly bore disturbances were detected only at the southernmost AWS stations. In all cases, the bores appeared to form within the trough at night and in some cases were found to move ahead of it.

The event of 13-14 October 2013 to be discussed in the next section is characterized by relatively strong ridging behind the trough line, which was pushed northeastwards as far as the southern coast line of the gulf.

Figure 3 shows time-series of a variety of meteorological parameters recorded by the AWS stations at Urandangi and Camooweal on 17 August 2013. On this day, the southerly bore was not seen at stations north of Camooweal. The onset of the bore at Urandangi at 0430 EST was marked by a 2 mb pressure jump, accompanied by wind gusts up to 7 m s^{-1} and a change in wind direction from northerly to one fluctuating between southwest and west-northwest. Following the bore onset, there were oscillations in pressure, wind speed and direction, typical of an undular bore, and the wind subsequently calmed. There was a slight rise in temperature also. Typically, the sudden increase in wind speed accompanying a bore brings about downward turbulent mixing of potentially warmer air from aloft (Smith *et al.* 1995).

About half an hour later, about 0500 EST, there began a progressive decline in both temperature and dew point temperature indicative of a cold front passage. At 0730 EST, the wind direction changed from west to southeast and the wind speed increased to 9 m s^{-1}. At the same time, the temperature increased rapidly from 16°C to 22°C and the dew point fell to about 0°C, suggestive of the passage of a ’dry line’. Some light into the meteorological situation accompanying these developments is shed by relevant fields extracted from ECMWF analyses discussed below.

The bore arrived at Camooweal, about 180 km north of Urandangi, at 0815 EST, but there, there is no obvious signature of an air mass change following the bore. After sunrise, as dry turbulent mixing becomes established, the stable inversion allowing bore propagation is progressively eroded over land and cold frontal signatures weaken (Smith *et al.* 1995, Reeder *et al.* 2000).

Reeder *et al.* (2000) found that despite losing much of their temperature signature during the daytime, cold

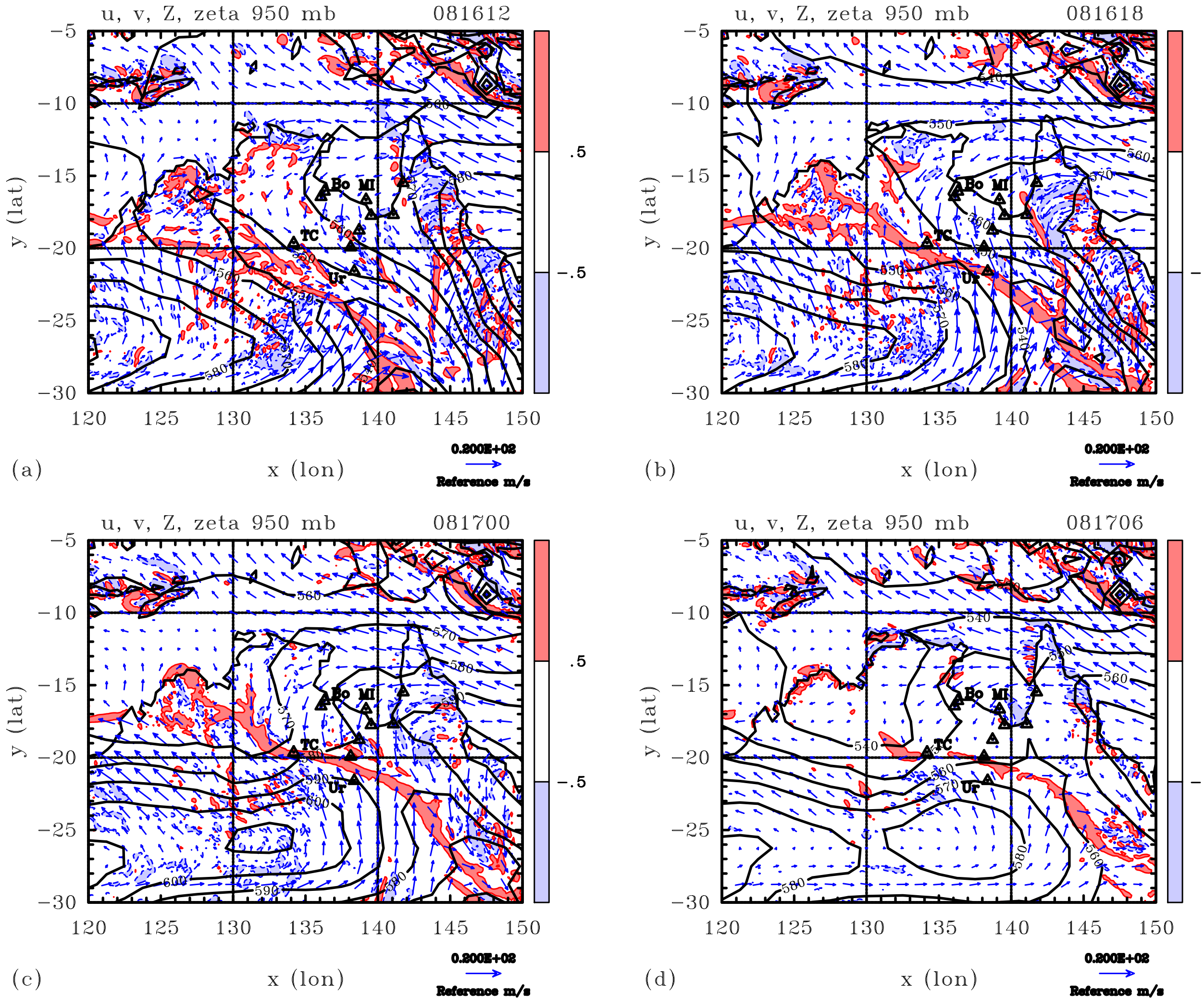

Figure 4. Relative vorticity, horizontal wind vectors and isopleths of geopotential height, Z, at 950 mb derived from the ECMWF analysis data at (a) 1200 UTC and (b) 1800 UTC on 16 August 2013, and (c) 0000 UTC and (d) 0600 UTC on 17 August 2013. Contour interval for Z is 1 dm. Cyclonic relative vorticity is plotted as positive with values larger than 0.5×10^4 s^{-1} shaded pink, areas of anticyclonic vorticity with values less than -0.5×10^4 s^{-1} shaded light blue. The lengths of the wind vectors are proportional to wind speed relative to the vector shown below each panel, which has a speed of 20 m s^{-1}.

fronts moving across the Australian continent could still be tracked by their signature in the low-level vorticity field, where they are seen as narrow strips of low-level cyclonic relative vorticity.

Figure 4 shows the vertical component of the relative vorticity field and wind vectors at 950 mb, together with the isopleths of geopotential at this [*], for a portion of the Australian continent at six-hourly intervals from 16 August 2013 1200 UTC to 17 August 2013 0600 UTC. These fields are obtained from the ECMWF analyses. On 16 August 2013 at 1200 UTC, there is a trough in the geopotential height contours coinciding approximately with the trough line marked in Figure 2 along the northern side of the ridge. In the ECMWF analysis, the geopotential trough is characterized (at the contour levels chosen) by broken strips of enhanced cyclonic vorticity and separates northwesterly flow ahead of the trough from strong southerly flow behind it. The strips of cyclonic vorticity are seen to extend as far as the west coast of the continent.

During the next twelve hours, the strips of cyclonic vorticity have moved northeastwards as the ridge advances and the trough has become less pronounced in the geopotential isopleths. At 1800 UTC (0400 EST), the strips of cyclonic vorticity have merged to a single prominent line that lies across the entire continent and is located just over Urandangi. About half an hour later, the AWS data show the passage of an undular bore at Urandangi followed by a further half an hour by the passage of a cold front.

At 0000 UTC, the strip of positive vorticity has moved further northeastwards and lies between Urandangi and Camooweal. Thereafter it becomes stationary and weakens considerably, presumably on account of day time convective heating. The undular bore arrived at Camooweal at 0815 EST, but the cold front was not detected there.

Figure 5 shows the potential temperature field and wind vectors at 950 mb together with the isopleths of geopotential at this level from the ECMWF analyses at the same times as in Figure 4. At 1200 UTC, a region of relatively strong temperature gradient is situated southwest of Urandangi and separates strong southwesterly flow to the south from a weaker northwesterly flow to the north of it. The northern edge of this region marks a cold front of southern origin.

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[*] The geopotential from the ECMWF analyses is converted from gpm to m by dividing by 9.8 m s^{-2}.

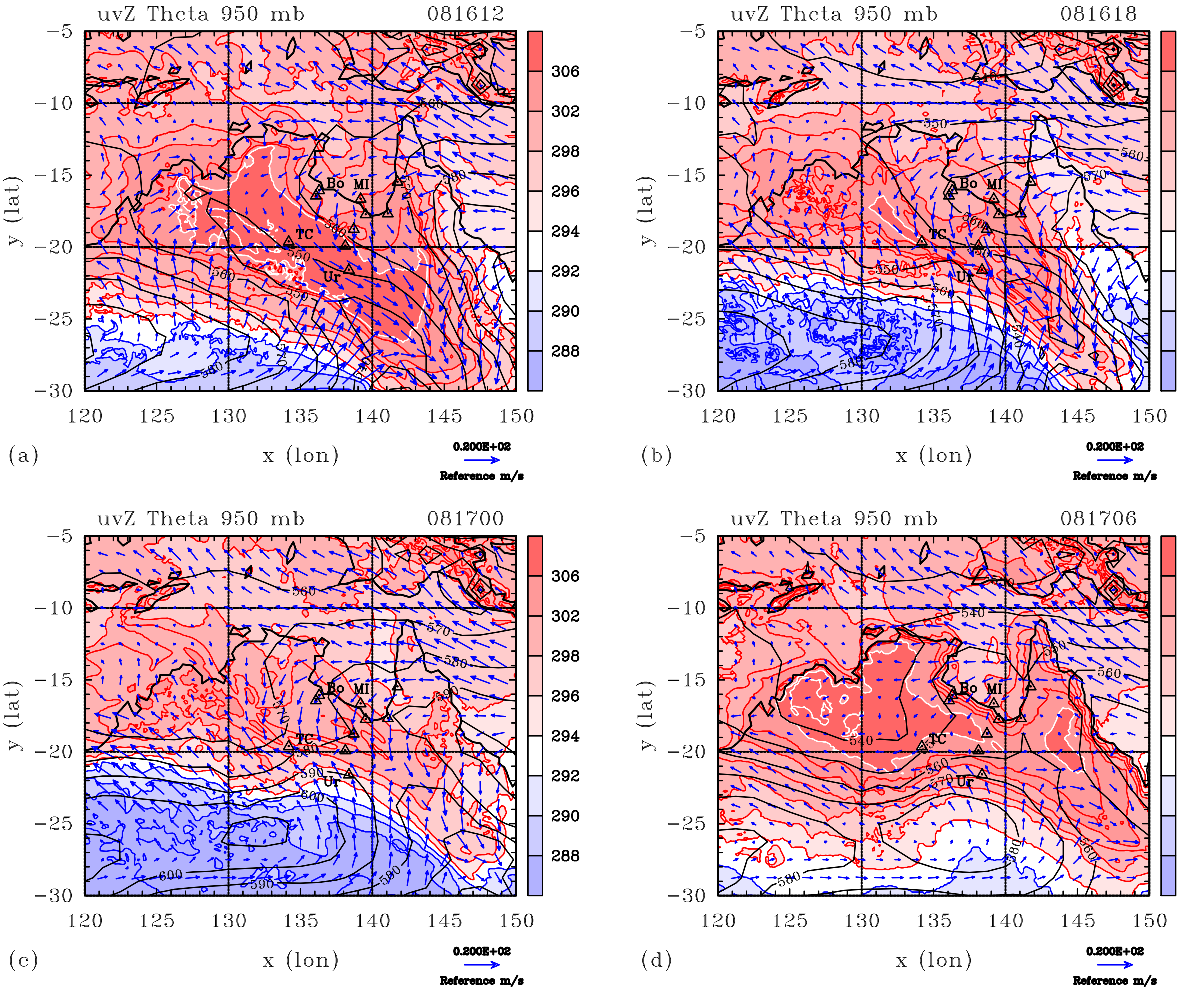

Figure 5. Contours of potential temperature θ in K, horizontal wind vectors and isopleths of geopotential height, Z, (in m) at 950 mb derived from the ECMWF analysis data at (a) 1200 UTC and (b) 1800 UTC on 16 August 2013, and (c) 0000 UTC and (d) 0600 UTC on 17 August 2013. Contour interval for Z is 10 m. Contour interval for θ is 1 K. Selected ranges of θ are colour shaded as indicated in the label bar. The lengths of the wind vectors are proportional to wind speed relative to the vector shown below each panel, which has a speed of 20 m s^{-1}.

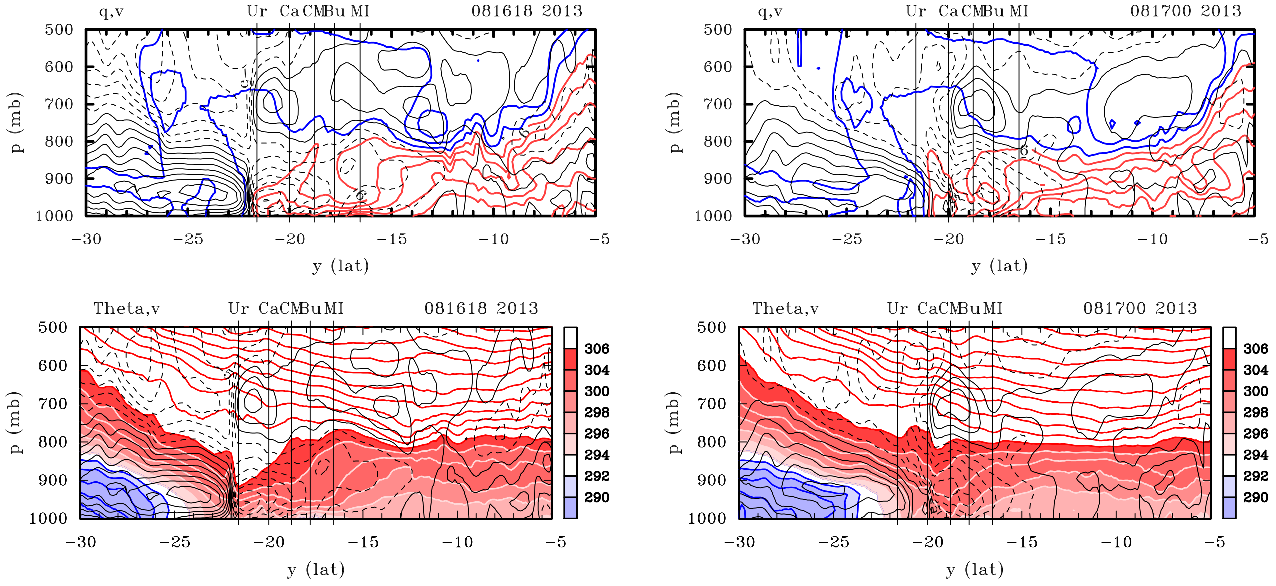

Figure 6. Vertical cross sections of specific humidity, q, (upper panels, isolines in blue/red) and potential temperature, θ, (lower panels, isolines in blue/red) at 16 August 2013 1800 UTC (left panels) and 17 August 2013 1000 UTC (right panels). Shown in each panel also are contours of the meridional wind component, v (black contours). Contour interval for q is 2 g kg^{-1}, for θ is 2 K and for v is 2 m s^{-1}. Selected ranges of θ are colour shaded as indicated in the label bar.

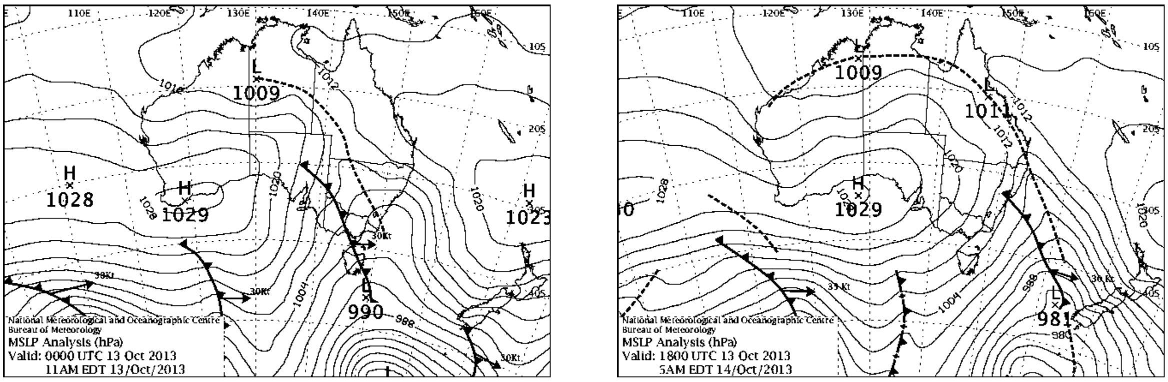

Figure 7. Bureau of Meteorology mean sea level isobaric analyses for the Australian region at 0000 UTC (left) and 1800 UTC (right) on 13 October 2013.

Another region of relatively strong temperature gradient marks the sea breeze front further to the northeast between Camooweal and Century Mine. Six hours later the cold front has moved towards the northeast and is located just over Urandangi. During the following day time, the frontal temperature gradient becomes more diffuse for reasons discussed above.

Vertical cross sections of specific humidity, potential temperature and the meridional component of wind velocity at 1800 UTC 16 August 2013 and 0000 UTC 17 August 2013 from the ECMWF analyses are shown in Figure 6. At 1800 UTC, southerly flow is sharply separated from northerly flow at about 22°S, i.e. a little south of Urandangi. At Urandangi, there is a strong meridional gradient in specific humidity separating moister air to the north from drier to the south. This gradient in specific humidity is presumably associated with the sea breeze front that has penetrated inland a little further south than Urandangi. The vertical cross section of potential temperature at 1800 UTC indicates that the sea breeze front collides with the cold front at about this time. At its leading edge, a little south of Urandangi, the isentropes are deflected upwards, which is indicative of lifting near the point of collision. Six hours later, the southerly flow has moved to the north of Urandangi, displacing the sea breeze to its north. Below 900 mb, daytime dry convective heating has led to a pronounced mixed layer in the potential temperature field.

Figures 4 to 6 indicate that the ECMWF analyses are able to capture the propagation of the cold front as far north as Urandangi, but they do not distinguish between cold font and bore. As might be expected, the horizontal resolution of the analyses is too coarse to capture the bore that developed during this night, presumably at the leading edge of the front.

3.2. *Event of 13-14 October 2013*

Figure 7 shows the synoptic situation for the Australian region on 13 October 2013, where a southerly bore was recorded at all stations from Urandangi to Mornington Island. In contrast to the case of 17 August 2013, a trough line is analysed across the whole continent and moves northeastwards from about 20°S to the coastline over a period of 12 h. This movement is accompanied by strong ridging over the whole continent.

Figure 8 shows similar time-series to Figure 3 at the four AWS stations at Urandangi, Camooweal, Century Mine and Burketown from 13 to 14 October 2013. At the southernmost stations, Urandangi and Camooweal, the passage of a cold front is marked by a progressive decrease in temperature and a clear wind change at 1430 EST and 1800 EST, respectively. At both stations, the wind speed increases sharply, reaching values up to 12 m s^{-1} and the wind direction turns from northwest to south. The passage of the front was recorded also at Tennant Creek at 1900 EST (time-series not shown).

A marked rise in dew point temperature at Century Mine is seen at 2000 EST, accompanied by an increase in the wind speed. These signatures indicate the passage of the sea breeze front from the south coast of the gulf. This is followed two hours later by a pressure jump of about 1.5 mb and a wind direction change from north to south. Thereafter, the wind direction fluctuates until about 2300 EST, when it becomes steady and from the south. At this time, there is an abrupt fall in dew point temperature, indicative of a dry air mass change, but no change in temperature. Evidently, the disturbance has lost the characteristics of a cold front.

At 0100 EST on the following day, the pressure jump is seen at Burketown. There, the disturbance has changed its structure from a single pressure jump at Century Mine to an undular bore with approximately six waves in the time-series for pressure, wind speed and direction. This disturbance is accompanied by a minor increase in temperature, presumably on account of the downward mixing of potentially warmer air at the leading edge of the bore, and a wind direction change to a southerly. Three hours later, at 0400 EST, the dew point temperature begins to fall, again indicating the dry line passage, but the temperature rises slowly.

The passage of the southerly bore was recorded also at Normanton Airport (0200 EST), McArthur (0300 EST) and Borroloola Airport (0400 EST) (not shown). The pressure time-series at the last two stations have between 6 and 10 undulations following the bore (not shown).

Figure 9 shows plots similar to Figure 4 at six-hourly intervals from 0000 UTC to 1800 UTC 13 October 2013. As in the event of 17 August 2013, a pronounced strip of cyclonic vorticity is co-located with a trough line and extends across the entire Australian continent. At 0000 UTC, parallel to and ahead of this strip, a second less prominent strip of cyclonic vorticity extends approximately between 130 °E and 142 °E, just to the north of Urandangi and appears to be associated with the sea breeze front from the gulf.

The time-series at Urandangi (see Figure 8) show a change in wind direction from south to north at 1000 EST

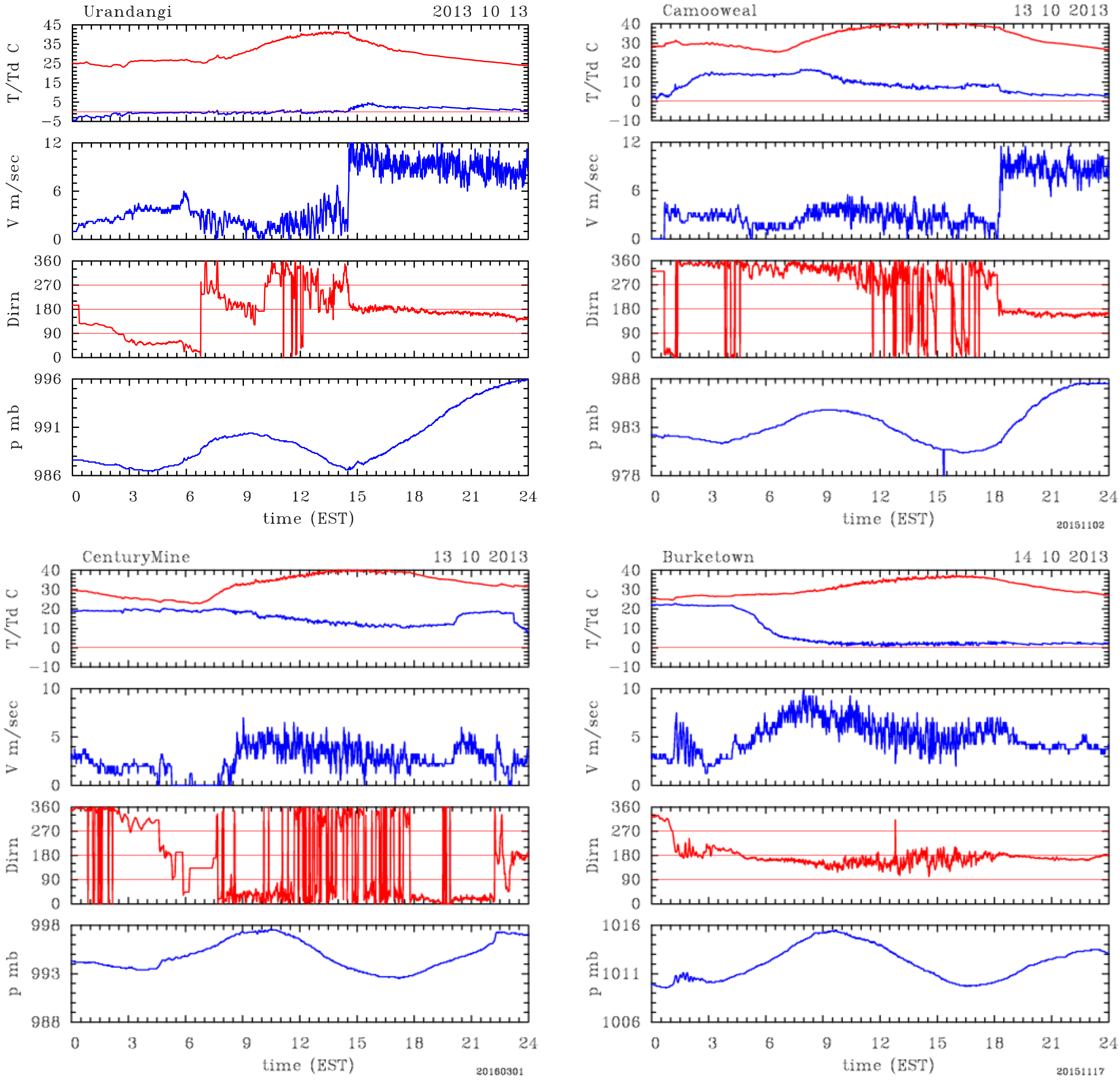

Figure 8. Time-series of temperature (T), dew point temperature (T_d), wind speed (V) and direction ($Dirn$), and pressure (p) observed by Bureau of Meteorology automatic weather stations at Urandangi (upper left), Camooweal (upper right), and Century Mine (lower left) on 13 October 2013, and at Burketown (lower right) on 14 October 2013.

(0000 UTC), which underpins this interpretation. Six hours later, at 0600 UTC, this second strip of cyclonic vorticity has weakened, more or less in situ. The more prominent strip of cyclonic vorticity that marks the frontal trough moves steadily northeastwards as far as the coast line during the time period shown, accompanied by strong ridging over the continent. At 0600 UTC, this strip is located over Urandangi. The air mass change that accompanies the passage of the trough line in the ECMWF analyses coincides approximately with the cold front passage at 1430 EST (0430 UTC) seen in the AWS data at Urandangi (see Figure 8).

At 1200 UTC, the strip of positive vorticity is located between Camooweal and Century Mine. The AWS data at Century Mine show a sharp pressure jump of about 1.5 mb at that time and a second disturbance one hour later with a change in wind direction to south and a sharp decrease in dew point temperature. This wind change appears to be associated with the passage of the trough line/vorticity strip.

The AWS time-series suggest that the southerly bore formed at the cold front somewhere between Camoweal and Century Mine and then separated from and moved ahead of the front. The time-series at Burketown show that the pressure jump eventually developed into an undular bore followed later by a dry line, presumably a remnant of the cold front. The timing of the dry line coincides with the line of cyclonic vorticity being located over Burketown at 1800 UTC (0400 EST) (see Figure 9).

Vertical cross sections of potential temperature and the meridional component of velocity in the ECMWF analyses from 0000 UTC to 1800 UTC on 13 October 2013 are shown in Figure 10. At 0000 UTC, a sharp gradient of potential temperature marking the leading edge of the cold front is located between 25°S and 24°S. South of Urandangi, the meridional velocity component is southerly and has a sharp gradient co-located with the cold front. The weakening of the temperature gradient and its northward progression during the next 18 hours is clearly discernible

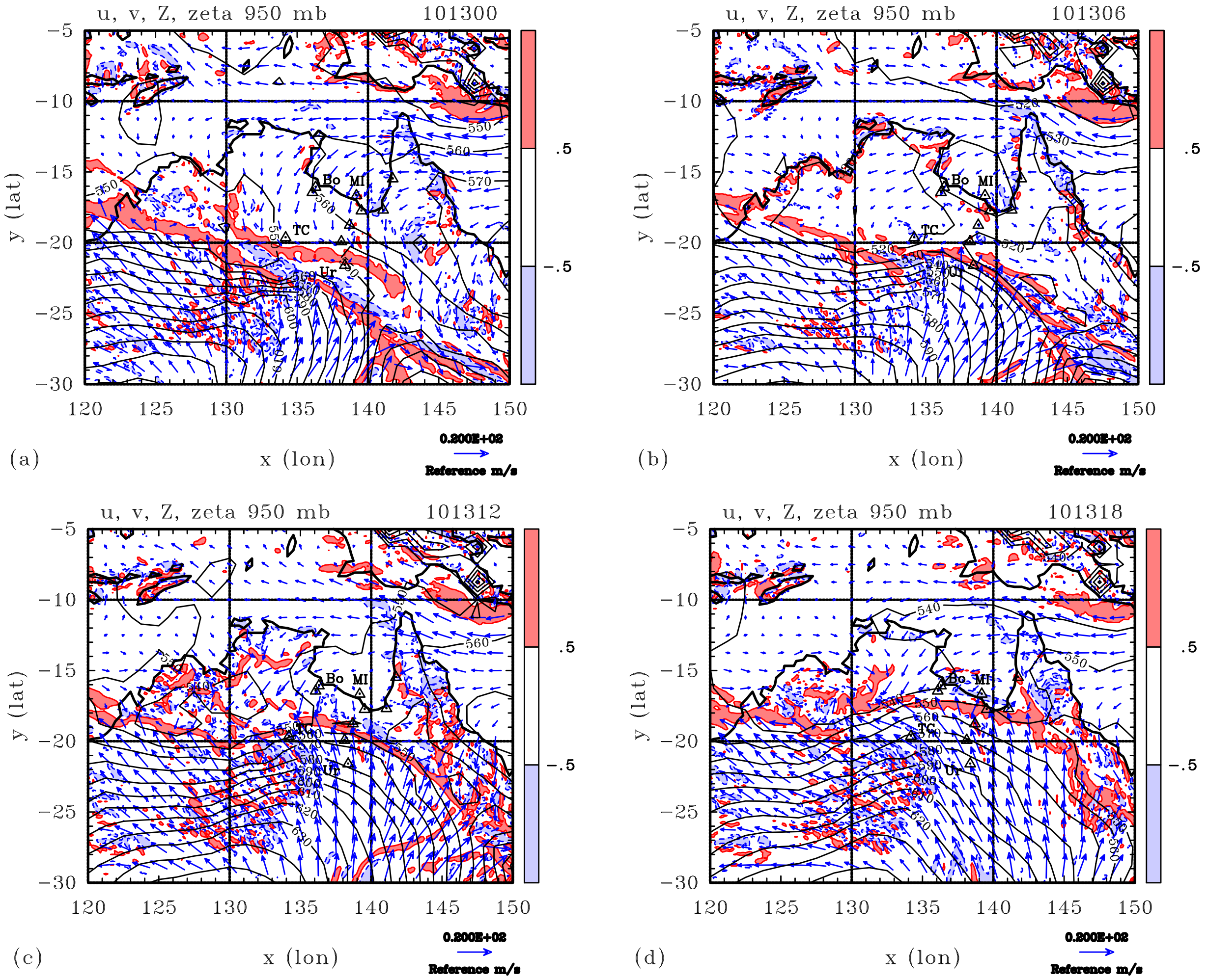

Figure 9. Relative vorticity, horizontal wind vectors and isopleths of geopotential height, Z, (in m) at 950 mb derived from the ECMWF analysis data at (a) 0000 UTC, (b) 1800 UTC, (c) 1200 UTC and (d) 1800 UTC on 13 October 2013. Contour interval for Z is 10 m. Cyclonic relative vorticity is plotted as positive with values larger than 0.5×10^4 s^{-1} shaded pink, areas of anticyclonic vorticity with values less than -0.5×10^4 s^{-1} shaded light blue. The lengths of the wind vectors are proportional to wind speed relative to the vector shown below each panel, which has a speed of 20 m s^{-1}.

from the cross sections. At 0600 UTC (1600 EST), a marked sea breeze front is seen near Burketown. At that time, the cold front is located just over Urandangi. Six hours later, the two fronts meet between Camooweal and Century Mine. By 1800 UTC (0400 EST on the next day), the southerly flow associated with the weakening cold front has almost reached Mornington Island.

In summary, the AWS data suggest that a bore developed at the leading edge of a cold front, somewhere between Camooweal and Century Mine. The bore moved ahead of the cold front and became undular as it crossed over the region south of the Gulf of Carpentaria, while the cold front weakened, transforming into a dry line. A similar event was well documented during the Central Australian Fronts Experiments (CAFE) (Smith *et al.* 1995). Again, the ECMWF analyses capture the cold front and its weakening, but not the bore.

3.3. *Events of 6 and 7 November 2012*

The synoptic situation for these events differs from that for the more typical cases of southerly bores exemplified above. The situations at 0000 UTC and 1800 UTC on 6 November 2012 in the MSLP analyses are shown in Figure 11. The main feature is a quasi-stationary trough that lies across the entire continent in a northwest-southeast-oriented direction and joins with the cold front associated with a low pressure system to the south of the continent. In contrast to the events in sections 3.1 and 3.2, ridging associated with a high pressure system centred over the Indian Ocean does not occur behind the trough line. At both 0000 UTC and 1800 UTC, another trough line is analysed parallel to and to the northeast of the first one and lies over the Northern Territory and Queensland. A trough in this location is often referred to as the inland trough.

The southerly bores that occurred on 6 and 7 November are seen in the AWS time-series at Urandangi and Camooweal in Figure 12. At Urandangi, the first disturbance occurred at 0400 EST 6 November where the wind turned from north to south-southwest and freshened sharply from about 2 m s^{-1} to 12 m s^{-1}. Shortly after the passage of the disturbance, the wind abated to values between 4 and 8 m s^{-1}. Unfortunately, pressure data are missing at Urandangi in 2012 so that the nature of the disturbance cannot be determined. There is a brief temperature rise of 2°C being followed by a continued decline in temperature until heating commences after sunrise. However, the disturbance brought about an abrupt rise in dew point temperature from 10°C to about 17°C.

At 0700 EST, a disturbance passed over Camooweal accompanied by a sharp pressure jump of 1 mb, an abrupt

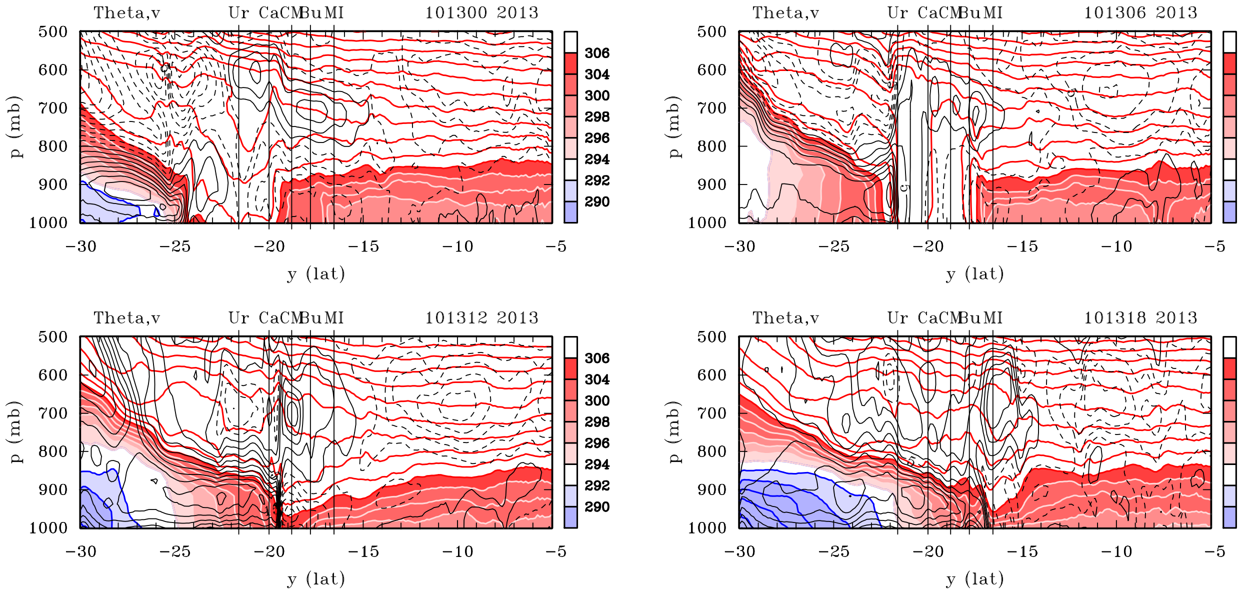

Figure 10. Vertical cross sections of potential temperature, θ, (isolines in blue, red or white) at 0000 UTC (upper left), 0600 UTC (upper right), 1200 UTC (lower left) and 1800 UTC (lower right) on 13 October 2013. Shown in each panel also are contours of the meridional wind component, v (black contours). Contour interval for θ is 2 K and for v is 2 m s^{-1}. Selected ranges of θ are colour shaded as indicated in the label bar.

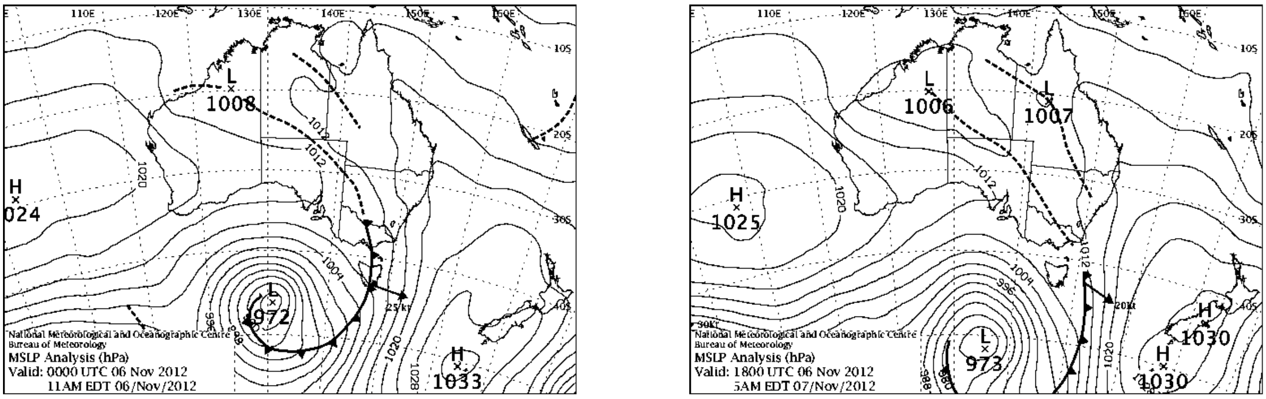

Figure 11. Bureau of Meteorology mean sea level isobaric analyses for the Australian region at 0000 UTC (left) and 1800 UTC (right) on 6 November 2012.

increase in wind speed from about 2 m s^{-1} up to 8 m s^{-1}, and a change in wind direction from north to south-southwest. The pressure jump was followed by a few oscillations in pressure. The disturbance structure at Camooweal is clearly undular-bore-like, but the bore is followed about three hours later, at 1000 EST, by a sharp wind change from an easterly to a southerly and the wind speed refreshens after a brief period of calm conditions. There is a rapid fall in pressure and temperature and simultaneous rise in dew point temperature. Again, the nature of this disturbance is hard to classify. At about 0900 EST, the wind direction changes from southerly to easterly and there is a further pressure rise. These features appear to be associated with the northeasterly Morning Glory seen also on this day in the time-series at Mornington Island, Burketown and Century Mine (not shown) and might explain the complexity of the disturbance at 1000 EST.

Later that day, the southerly flow at both stations is replaced by light easterly wind at 2015 EST (Urandangi) and 2230 EST (Camooweal), respectively. A second southerly disturbance is seen at Urandangi at 2330 EST 6 November, where the wind speed increases and the wind direction turns from north to south-southwest, but there is no obvious air mass change. Early the next morning, at 0300 EST, this disturbance passes over Camooweal (lower panel of Figure 12) with sharp pressure jump of about 0.5 mb followed by several pressure undulations and fluctuations in wind speed. Again, the wind direction turns from north to south-southwest. Like the first disturbance at Camooweal on the previous day, this disturbance has the character of an undular bore.

Figure 13 shows ECMWF analyses similar to Figure 4 from 1800 UTC on 5 November to 1800 UTC on 6 November. Strips of cyclonic vorticity are co-located with each of the trough lines analysed in the two mean sea level isobaric charts in Figure 11. The south-westernmost strip remains quasi-stationary during the 24-hour period shown, whereas the one to the northeast moves a little northeastwards. These two strips are separated by a light-wind region associated with a mesoscale anticyclone in the geopotential field. A third line of cyclonic vorticity is seen intersecting the southeast corner of the gulf. This line is associated with the northeasterly Morning Glory on 6 November (EST) that was observed on 6 November (EST) at Mornington Island, Burketown and Century Mine.

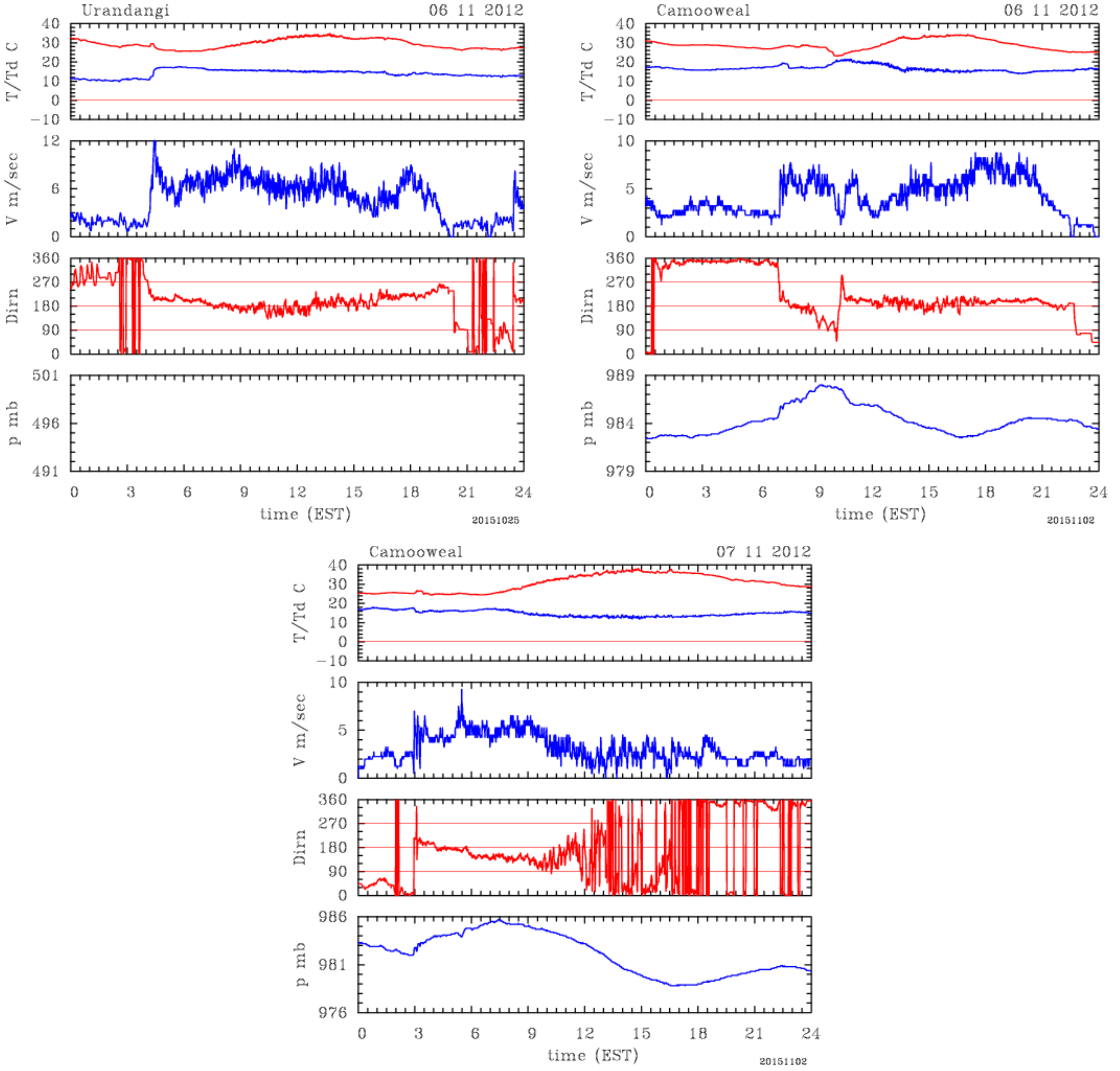

Figure 12. Time-series of temperature (T), dew point temperature (T_d), wind speed (V) and direction ($Dirn$), and pressure (p) observed by Bureau of Meteorology automatic weather stations at Urandangi (upper left) and Camooweal (upper right) on 6 November 2012, and at Camooweal (lower) on 7 November 2012.

At 1800 UTC on 5 November, the strip of cyclonic vorticity ahead of the mesoscale anticyclone lies a little northeast of Urandangi. The AWS data at this station show a disturbance with wind direction changing from north to south at about the same time (see upper left panel of Figure 12). Six hours later, at 0000 UTC, the strip of cyclonic vorticity has moved northeastwards and is located just over Camooweal. There, as noted above, the AWS data show a wind change and pressure fall at this time, but no evidence of an air mass change (upper right panel of Figure 12).

Figure 14 shows vertical cross sections similar to those in Figure 10 from 1800 UTC 5 November to 1800 UTC 6 November. In contrast to the cases described earlier, no cold front is discernible in the cross sections and there must be another mechanism by which the southerly bores on these two days have been generated.

At 1800 UTC on 5 November, the air lying over the continent between Urandangi and the coast (a little south of Mornington Island) is stably stratified as a result of the inland penetration of sea breeze air. Above it, the stratification is relatively weak, a remnant of convective mixing during the day time, providing a wave-guide suitable for bore propagation. South of Urandangi, between about 27.5°S and 21.6°S, there is a region of low level southerly flow with maximum speed at a pressure altitude near 920 mb. The low altitude suggests that this flow is a nocturnal jet (e.g. Garratt 1985, Garratt and Physick 1985, May 1995) that formed within the mesoscale anticyclone. At Urandangi, the meridional component of velocity shows a strong gradient. At the same time, the AWS observations show a wind direction change from north to south and a sharp increase in wind speed, which is presumably the wind surge at the leading edge of the nocturnal jet. Figure 14 suggests that the undular bore seen at Camooweal was generated by this nocturnal jet. At 0000 UTC, the region of southerly flow has moved further northwards, but the wind speed and its gradient have weakened. During the evening and the following night, the region of southerly flow is

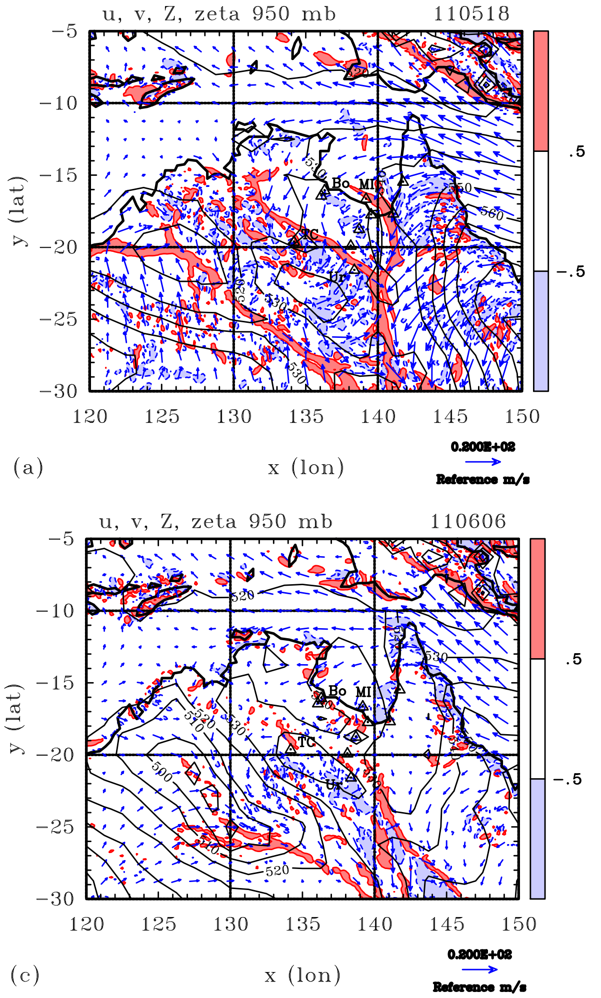

Figure 13. Relative vorticity, horizontal wind vectors and isopleths of geopotential height, Z, (in m) at 950 mb derived from the ECMWF analysis data at (a) 1800 UTC on 5 November 2012, and (b) 0000 UTC, (c) 0600 UTC and (d) 1200 UTC on 6 November 2012. Contour interval for Z is 1 dm. Cyclonic relative vorticity is plotted as positive with values larger than 0.5×10^4 s^{-1} shaded pink, areas of anticyclonic vorticity with values less than -0.5×10^4 s^{-1} shaded light blue. The lengths of the wind vectors are proportional to wind speed relative to the vector shown below each panel, which has a speed of 20 m s^{-1}.

more confined and lies between a little south of Urandangi and north of Camooweal (see lower panels of Figure 14). At 1800 UTC on 6 November, the maximum meridional component of velocity lies at about 950 mb just a little south of Camooweal, suggesting that the nocturnal jet played a role in generating the southerly undular bore detected about one hour earlier (0300 EST) at this station.

In their early study of southerly nocturnal bores, Smith *et al.* (1986) hypothesized that many southerly wind surges and bores in this region are produced by the interaction of the inland nocturnal jet and the sea breeze front along the southern coast of the Gulf of Carpentaria. This hypothesis finds support in the two November cases described here, but the details of the interaction cannot be captured by the ECMWF analyses as their resolution is too coarse. A numerical simulation using a mesoscale model would be necessary to obtain more insight into the details of the generation mechanism of the southerly bores on these two days.

4. Other cases

The synoptic situation for the other eight events summarized in Table I is characterized by features similar to those during the two events described in sections 3.1 and 3.2, where there is ridging across the continent behind a shallow cold front. As in the event of 17 August 2013, the ridging behind the front is weak both during the events of 30 August 2012 and 26 September 2013. On these days, southerly bores were recorded only at one of the two southernmost stations (Urandangi or Camooweal).

The event of 28-29 September 2012 is very similar to that of 13-14 October 2013 described in section 3.2. In these, the southerly bore and the cold front moved northeastwards overnight as far as the southern coast line of the gulf, followed by strong ridging to the south. In each case, the bore could be traced from Urandangi to Burketown.

In two other cases ridging across the continent was moderately strong, although the front reached the AWS stations network in the early morning. On 11 October 2013 a southerly bore was recorded at the AWS stations in Urandangi, Camooweal and Century Mine, but not at any stations further north. Is is likely that the low-level stable layer that serves as a waveguide for these waves was destroyed by convective heating after the southerly bore passed over Century Mine at 0700 EST. Similarly, the southerly bore that developed on 24 September 2014 passed over Urandangi at 0630 EST and were not recorded elsewhere.

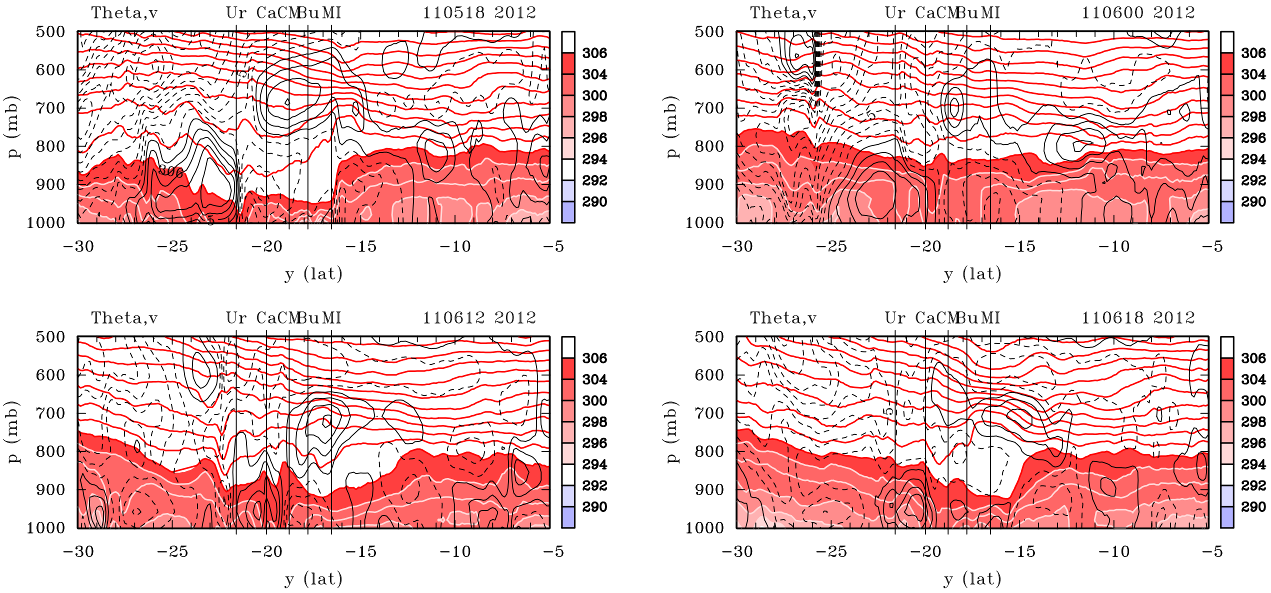

Figure 14. Vertical cross sections of potential temperature, θ, (isolines in blue, red or white) at 1800 UTC (upper left) on 5 November 2012, and 0600 UTC (upper right), 1200 UTC (lower left) and 1800 UTC (lower right) on 6 November 2012. Shown in each panel also are contours of the meridional wind component, v (black contours, positive values, solid, negative values dashed). Contour interval for θ is 2 K and for v is 2 m s^{-1}. Selected ranges of θ are colour shaded as indicated in the label bar.

Two further events (1 August 2014 and 2 September 2014) are characterized also by strong ridging over the continent. However, the frontal trough that originated from a low pressure system centred over the sea south of Tasmania did not extend far to the north. Thus, the southerly bores that formed on these days passed over the southernmost stations at Urandangi and Camooweal only.

5. Conclusions

We have analysed one-minute data from AWSs in the Gulf of Carpantaria region for the period 1 August to 31 December during the three years 2012 to 2014. A total of twelve days were identified (four per year) on which a southerly bore passed over at least one station, corroborating the results from the observational study by Nudelman *et al*., who found five southerly bore occurrences from August to November 2006. Six of the bores were followed some hours later by a clear air mass change.

Four cases of southerly bores were analysed in detail. The meteorological setting for these events was examined using various fields extracted from European Centre for Medium range Weather Forecasts (ECMWF) analyses, supplemented by Bureau of Meteorology MSLP analyses. Two of the bores formed under synoptic conditions that have been identified previously as being particularly favourable for the development. On both days, a pronounced frontal trough was sandwiched between two broad high pressure systems, one centred over the Indian Ocean and the other east of the Australian continent. In both cases, the trough was oriented in an approximately northwest-southeast direction across the Northern Territory and Queensland and moved northeastwards as the ridge over the continent strengthened from the west. One difference between the two events lies in the timing of trough movement through the AWS network. In one case, the frontal trough crossed Urandangi in the early morning and the southerly bore did not propagate further north of Camooweal, presumably because day time convective heating destroyed the nocturnal stable layer on which the bore was propagating. In the other case, the frontal trough crossed the southernmost AWS stations in the late evening and the bore that developed within this trough propagated much further towards the coastline during the night.

In the two other cases examined in detail, the synoptic situation was different from that in all the other ten cases. Much of the continent was dominated by low pressure with a quasi-stationary frontal trough extending from a heat low located over northwestern Australia to a mid-latitude cold front associated with a low south of the continent. On both mornings, a southerly bore developed within a second (inland) trough to the northeast of the frontal trough and was recorded at the AWS stations at Urandangi and Camooweal. A mesoscale ridge developed behind the second trough and the associated low-level nocturnal jet appears to have played a role in the generation of these bores as in the cases with a frontal trough.

It was found that the ECMWF analyses are able to capture the troughs as well as the timing of their passage through the AWS network. In the four cases examined in detail, the troughs were seen as narrow strips of elevated cyclonic vorticity at 950 mb in the ECMWF analyses and structural characteristics of a shallow cold front were evident in vertical cross sections intersecting the troughs. Nevertheless, the horizontal resolution of these analyses is too coarse to capture the generation of the bores.

Future work would include a numerical simulation of some of the cases described in this study in order to investigate the precise generation mechanism of southerly bores by subtropical cold fronts.

6. Acknowledgements

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