Observations of a cut-off low over southern Australia

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SUMMARY

The structure and evolution of an intense cut-off low is documented in detail unprecedented for the Australian region, by combining high time-resolution radiosonde profiles with co-located wind-profiler observations and routine Australian Bureau of Meteorology analyses. The cut-off low develops over the ocean south of Australia and subsequently interacts with a subtropical frontal system over the central part of the continent. Throughout the period of observation, the strongest temperature gradients lay through the subtropics. Moreover, the subtropical temperature gradients strengthened while the midlatitude temperature gradients associated with the cut-off low weakened. The Australian Bureau of Meteorology’s 150 km Regional Assimilation and Prognosis System analyses capture the broad-scale structure and evolution of the system reasonably well. The system documented here is similar in structure to the instant occlusion investigated by Browning and Hill (1985), the major difference being that our cut-off low develops poleward of a subtropical front. The cut-off low was cold-cored and produced a very deep tropopause fold. Over Adelaide, the tropopause descended to an altitude of about 5 km, and the temperature at 500 hPa fell to -30 °C. The western edge of the low-level cold dome was marked by a strong secondary warm front, which passed over Adelaide about 8 hours after the tropopause height minimum. The warm front was characterized at the surface by an absolute minimum in the pressure, and a temperature rise of about 7 °C. Significantly, this increase in temperature took place in the early hours of the morning, against the diurnal trend. The cut-off low produced very high rainfall, resulting in flash flooding and much damage in the Adelaide Hills area. The most severe convection took place in the region behind the lowered tropopause, around the passage of the warm front.

KEYWORDS: Instant occlusion Radiosonde Tropopause fold Wind profiler

1. INTRODUCTION

Late in August 1992, an intense cut-off low developed to the south of Australia and interacted with a subtropical cloud band oriented north-west to south-east across the continent. Such cloud bands are known locally as north-west cloud bands. The subsequent passage of this system across the south-eastern part of Australia coincided with the final stages of the South Australian Fronts EXperiment (SAFEX), a collaborative field programme involving the Centre for Dynamical Meteorology and Oceanography at Monash University, and the Department of Physics and Mathematical Physics at the University of Adelaide. During SAFEX, radiosondes with Omega wind-finding capability were released from the Buckland Park Research Station near Adelaide. In addition, a VHF wind-profiling radar at Buckland Park was operated continuously throughout the experiment. These data, combined with automatic weather station records at Buckland Park, routine Australian Bureau of Meteorology measurements and synoptic analyses, enable us to document the structure and evolution of the cut-off low in detail unprecedented for the Australian region.

The cut-off low caused major flash flooding in the Mt. Lofty Ranges, killing two people when a caravan park near Cudlee Creek (25 km north-east of Adelaide) became flooded. Strong winds and floods caused damage of over ten million dollars to houses, roads and bridges (Furler 1993). Recently, Mills and Wu (1995) analysed this event in some detail. They based their study on the operational synoptic analyses, and they focussed principally on the large-scale conditions that forced the region of severe convection. In addition, Bourke et al. (1995) have used this event as a test case for the Australian Bureau of Meteorology’s Global ASSimulation and Prediction scheme (GASP).

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The sparseness of routinely available observations is, perhaps, the key difficulty faced by those wishing to study synoptic and mesoscale weather systems in the Australian region (or for that matter anywhere in the southern hemisphere). The routine observational network over virtually the entire continent is only just adequate for detailed synoptic studies, and totally inadequate for investigations of mesoscale phenomena. Not surprisingly, there have been few previous observational studies of extratropical cyclogenesis in the Australian region, and those that have been undertaken have been based almost entirely on routine Australian Bureau of Meteorology analyses and satellite imagery.

The first such study of which we are aware is that by McRae (1955) who investigated surface cyclogenesis associated with an upper cut-off low. Later, Downey et al. (1979) combined satellite imagery, radiosonde data and conventional analyses to study the rainfall from a low-pressure system over southern Australia. Their aim was to test whether higher resolution and more frequent satellite images could be used to give accurate short-term rain forecasts. The system studied by Downey et al. had many features in common with that described in this paper; in particular, they documented a tropopause fold above the surface low, a strong upper-level jet to the north of the low, a weak north-west cloud band and heavy rainfalls. Ryan and Meadows (1979) investigated a cut-off low over south-eastern Australia with the principal aim of identifying its potential for cloud seeding. At the time of their study, the Bureau of Meteorology’s analysis scheme had a resolution of 250 km and only 5 levels in the vertical. Next, Holland et al. (1987) focussed on the development of east-coast cyclones. These are a class of relatively rare but very intense storms that form during winter on the east coast of Australia; a necessary condition for their development appears to be a trough in the easterly flow over eastern Australia. Velden and Mills (1990) studied an intense extratropical cyclone which passed over southern Australia in December 1989. This storm produced very heavy rainfall and extremely low surface temperatures. These authors focused on the upper-level structure, particularly the circulation associated with two upper-level jets, and drew analogies between their storm and the northern-hemisphere case investigated by Carlson (1980). Mills and Russell (1992) examined another very-high-rainfall producing extratropical cyclone over eastern Australia. In contrast to the system investigated in the present paper, Mills and Russell’s system appeared to be of tropical origin. The only other study of which we are aware is the unpublished work of Bell (1982).

As the resolution of the routine observational network is so coarse, specially designed field programmes are necessary to document the morphology of synoptic and mesoscale weather systems in the Australian region. The principal aim of the present study is to document the structure of the cut-off low observed during SAFEX in as much detail as possible. This is the first study of an extratropical cyclone in the region to make use of relatively high-density radiosonde and wind-profiler observations. These special observations are combined with routine Australian Bureau of Meteorology analyses to provide a comprehensive picture of the system. Thus, our study builds on the work of Mills and Wu (1995). A related aim of the study is to compare the observed structure with that analysed by the Australian Bureau of Meteorology and discussed by Mills and Wu. Such a comparison helps verify the analysis scheme and determine the degree to which analyses can be used in this and other case-studies. This is especially important in regions like Australia where there are relatively few routinely available observations.

The remainder of the paper is arranged as follows. The data used for this study are described briefly in section 2. Following that, section 3 provides an overview of the synoptic situation using the Australian Bureau of Meteorology analyses and GMS* satellite

* Geostationary Meteorological Satellite.
images. Section 4 focuses on the mesoscale aspects of the event using the radiosonde and wind-profiler data collected during SAFEX. We summarize our observations in section 5.

2. Data

The Buckland Park 54.1 MHz wind profiler is described in detail by Vincent et al. (1987). It is located about 35 km north of Adelaide (34°37'S, 138°29'E) on a flat coastal plain. The only significant hills in the region are the Mt. Lofty Ranges (500–700 m above sea level) which lie about 50 km west of Buckland Park. The peak output power of the profiler was upgraded to 16 kW for SAFEX. During the experiment, the mode of operation involved vertical-beam Doppler estimates of the vertical velocity, and spaced-antenna measurements of the horizontal wind field, at five-minute resolution. The profiler took measurements between 2 km and 15 km altitude with a vertical resolution of 500 m. In the present study, only three-hour averages of the vertical velocity data are presented. A Vaisala MARWINsone system provided smoothed profiles of pressure, temperature, humidity and wind every 50 m up to a height of 20 km. These radiosondes were tracked using the Omega position-finding system. Eighteen radiosondes were launched over 64 hours during the intensive observing period (IOP), which ran from about 1400 UTC 28 August 1992 to 0900 UTC 31 August 1992 (Local Standard Time at Adelaide = UTC + 9.5 hours). In the 24-hour period prior to the beginning of the IOP, these data were supplemented by the routine 12-hourly Bureau of Meteorology radiosondes, released at Adelaide Airport 40 km to the south of Buckland Park. The Adelaide Airport radiosondes provided thermodynamic information of the same quality as that returned by the radiosondes released from Buckland Park, but were tracked using conventional radar. Hence, the calculated winds are of a much poorer quality than those from the Buckland Park radiosondes, and therefore are not used in the analysis presented here. An automatic weather station measuring temperature, pressure, wind speed and direction at a height of 1.5 m was installed at Buckland Park.

The VHF wind-profiler and radiosonde observations are supplemented by the analysed fields from the Bureau of Meteorology’s Regional ASsimilation and Prognosis system (RASP). At the time of the experiment, RASP had a resolution of 150 km with 15 pressure levels in the vertical, although it has since been upgraded. See Mills and Seaman (1990) for further details of the model.

3. Synoptic analysis

The cut-off low documented here developed on 27 August 1992 from a short-wave disturbance within a long-wave trough and cold air mass south-west of Australia. Figure 1 shows a sequence of six infrared satellite images of the Australian region at 12 hourly intervals starting from 1130 UTC 27 August. The satellite images are taken from Mills and Wu (1995). Early in the period (Figs. 1(a), (b)), the short-wave disturbance appears in the satellite imagery as a pronounced baroclinic leaf (marked ‘F’). The baroclinic leaf subsequently rotates cyclonically and assumes an (inverted) comma shape characteristic of midlatitude cyclones (marked ‘C’ in Figs. 1(d), (e)). In addition to the baroclinic leaf, a cold-frontal cloud band lies across the south-eastern-most part of Australia at 1130 UTC 27 August. This cloud band subsequently moves eastward and weakens, playing no direct part in the event to be described here. More information about the origin of the system can be found in Mills and Wu.

The first two images of the satellite sequence also show a developing north-west cloud band (marked ‘B’), over the north-western and central parts of the continent. The general features of north-west cloud bands have been described by Downey et al. (1981),
Bell (1982), Tapp and Barrell (1984), and Kuhnel (1990). Over the next 24 hours, the north-west cloud band thickens and extends southwards across Australia, developing a pronounced baroclinic-leaf structure in its eastern-most section and eventually merging with the comma cloud (Figs. 1(d), (e), (f)). Figure 1 also shows that the north-west cloud band's southern edge is more distinct than its northern edge, that the cloud tops are higher to the south-east than the north-west, and that the cloud curves anticyclonically in the eastern part of the band. Calculation of cloud-top temperatures shows the north-west cloud band comprised upper-level cloud whereas the top of the comma cloud was located in the mid-troposphere.
Four sequential twelve-hourly mean-sea-level pressure and 900 hPa temperature analyses are shown in Fig. 2; they begin 24 hours after the start of the satellite sequence described above. The light shading in Fig. 2 marks those regions in which the 900 hPa temperature gradient is between $1 \times 10^{-5}$ K m$^{-1}$ and $2 \times 10^{-5}$ K m$^{-1}$, while the dark shading marks 900 hPa temperature gradients greater than $2 \times 10^{-5}$ K m$^{-1}$. Two distinct regions of pronounced temperature gradient are analysed at 1100 UTC 28 August (Fig. 2(a)). The first band runs through central Australia. The leading edge of this feature, which we refer to as the subtropical front, is closely associated with the north-west cloud band. The second band of pronounced temperature gradient is oriented north-west to south-east across the south-western part of the continent. The leading edge of the northern section of this band defines a weak extratropical cold front. A pronounced surface low is analysed over the ocean south of Australia in the cooler air poleward of the subtropical front. Relatively high temperatures are analysed in the northerly airstream just east of the surface trough axis. The maximum temperature gradient lies just to the south-west of the low-pressure centre, and marks the warm front.

The warm sector of the surface low narrowed between 2300 UTC 28 August and 1100 UTC 29 August (Figs. 2(b), (c)). At the same time, strong cold advection and deformation provided by the cut-off low and strong ridge that extended across the continent, strengthened the subtropical front. In contrast, the extratropical cold and warm fronts weakened during the same period. By 1100 UTC 29 August the cut-off low had become well developed and the fronts, although weak, had assumed a ‘T-bone’ configuration characteristic of intense marine cyclones over the North Atlantic (see Shapiro and Keyser 1990). At this stage, the tropopause over Adelaide had descended to about 5 km above ground level and the temperature at 500 hPa had fallen to $-30$ °C. Below the tropopause fold lay a very cold, potentially unstable air mass. The 900 hPa temperatures above the surface trough had also fallen considerably, as a cold air stream wrapped around the north-western flank of the low. We refer to this air stream as the cold tongue. Relatively warm moist air, referred to as the warm tongue, had been advected around the low’s south-eastern side. The RASP analysis of the 900 hPa temperatures presented here verifies well against temperatures measured by the radiosondes released from Buckland Park.

The surface low deepened to an analysed minimum pressure of 978 hPa by 1100 UTC 29 August. Its maximum deepening rate was about 14 hPa during the 24-hour period from 1100 UTC 28 August to 1100 UTC 29 August, and does not, therefore, satisfy the bomb criterion of Sanders and Gyakum (1980)*. The low moved only slowly eastward, so that by 2300 UTC 29 August (Fig. 2(d)) the trough tilted north-east to south-west. By the end of the period, a strong ridge had developed across central Australia.

By 1130 UTC 29 August, the north-west cloud band and comma cloud associated with the cut-off low had overlapped (Fig. 1(e)), the combined cloud pattern resembling that of an occluded extratropical cyclone. In the cloud pattern, however, the subtropical front plays the role of the classical cold front, the north-west cloud band being analogous to the classical warm-conveyor-belt cloud. Similarly, the warm tongue, which flows under the north-west cloud band at right angles, plays the part of the classical cold-conveyor belt in the conceptual models of occluded extratropical cyclones. In fact, Mills and Wu (1995) refer to the warm tongue as the ‘cold-conveyor belt’. From this perspective, the structure of the system is very similar to the instant occlusion‡ documented by Browning and Hill (1985), their polar front and polar trough being analogous to our subtropical front and cut-off low.

* Sanders and Gyakum define bombs as extratropical cyclones with deepening rates exceeding 24 hPa over a 24-hour period.
‡ Browning and Hill use the term pseudo-occlusion.
Figure 2. RASP analyses of mean-sea-level pressure (solid) and 900 hPa temperature (dashed) for (a) 1100 UTC 28 August 1992, (b) 2300 UTC 28 August, (c) 1100 UTC 29 August, and (d) 2300 UTC 29 August. Contour intervals are 4 hPa and 3 K. The light and dark shaded regions show respectively where $1 \times 10^{-5}$ Km$^{-1} \leq |\nabla_{900 \text{ hPa}} T| \leq 2 \times 10^{-5}$ Km$^{-1}$ and $|\nabla_{900 \text{ hPa}} T| \geq 2 \times 10^{-5}$ Km$^{-1}$. Adelaide is marked on Fig. 2(a); Buckland Park is located 35 km north of Adelaide.
Figure 2. Continued.
By 2300 UTC 29 August, the leading edge of the warm tongue, which was to the south of Adelaide 12 hours earlier, had been advected around the western side of the cut-off low and over Adelaide (Fig. 2(d)). At the same time, the leading edge of the cold tongue had become isolated, forming a cold pool over south-eastern Australia. Note that the western and eastern boundaries of the cold pool are marked by regions of relatively strong temperature gradient. These gradients define secondary warm fronts and cold fronts respectively. The strong warm advection by the warm tongue on the western side of the low appears to have concentrated the temperature gradient there, producing a strong secondary warm front. Figure 2(d) shows that by 2300 UTC 29 August the low had developed two troughs, one oriented along the south-east coast of Australia and the other oriented northward from the low centre; these troughs are associated with the cold front and secondary warm front respectively. The primary warm front, located south-east of the low, had by this stage weakened greatly.

Between 2330 UTC 28 August and 1130 UTC 29 August, a well developed hook-shaped cloud, or cloud head (marked A in Figs. 1(e), (f)), formed south-west of Adelaide near the boundary of the warm and cold tongues. The cloud head subsequently circulated around the low. The severe convection that led to flash flooding in the Adelaide Hills occurred around 1930 UTC, as the rear of cloud head moved across the coast and encountered the hills to the north-west of Adelaide (Mills and Wu 1995). The remnants of the cloud head, marked A, can be seen in Fig. 1(f). A cloud-free zone, or dry slot, associated with the cold tongue had developed to the rear of the comma cloud by 1130 UTC 29 August.

Figure 3 shows the 300 hPa geopotential height and the isotachs on this surface at 1100 UTC 29 August. The closed contour at 300 hPa indicates that the system was deep and cut off. A diffuential trough and strong upper-level jet streak are evident in this figure, with the wind speeds in the jet core exceeding 80 m s\(^{-1}\) in the analysis. At this time the surface low was located beneath the jet exit on its poleward side, and a strong upper-level ridge extended along the east coast of Australia.

A delta-shaped cloud, wedged between the north-west cloud band and the comma cloud, was visible over much of south-eastern Australia between 0400 UTC and 1630 UTC 29 August. Feren (1995) observed that clouds such as these were often precursors to strong surface development. In our case, the delta-shaped cloud appeared to form about 15 hours before the surface pressure had reached its minimum value, consistent with Feren's hypothesis. Of particular interest are the wave-like features in the cloud which we believe to be produced by gravity waves (Fig. 1(e)). These wave-like features were observed on the poleward side of the upper jet in a region of diffuence (Fig. 3).

The height of the 310 K isentropic surface and contours of potential vorticity (PV) on this surface are shown in Figs. 4(a) and 4(b) respectively. The system-relative wind vectors on the 310 K isentropic surface are plotted in each panel. The system speed was calculated from the position of the surface low-pressure centre at 6-hourly intervals. However, the pattern of system-relative wind vectors was found to be relatively insensitive to the speed of the system. The light shaded area in Fig. 4(b) marks where the 310 K isentropic surface intersects the tropopause, and the dark shaded area highlights that part of the surface located in the stratosphere. In line with the ideas of Hoskins et al. (1985), the cut-off low is characterized at upper levels by a strong, isolated, cyclonic PV anomaly positioned above the surface low. The evolution of the PV field has been discussed by Mills and Wu (1995). These authors showed that at upper levels there was warm-air advection ahead of the PV anomaly followed by cold-air advection behind, a pattern of temperature advection which often accompanies deep tropopause folding (Boyle and Bosart 1986). Weaker cyclonic PV anomalies are aligned with the subtropical front at lower latitudes.
Figure 3. RASP analyses (see text) at 1100 UTC 29 August 1992 of the height of the 300 hPa surface and isotachs on this surface. Contour intervals are 100 m and 10 m s\(^{-1}\). Regions where the wind speed exceeds 60 m s\(^{-1}\), 70 m s\(^{-1}\) and 80 m s\(^{-1}\) are shaded; the darker the shading, the greater the wind speed. Adelaide is marked; Buckland Park is located 35 km north of Adelaide.

4. **Mesoscale Observations and Analysis**

(a) **Surface features**

Time series of the pressure, temperature, wind speed and wind direction from the automatic weather station at Buckland Park Research Station are plotted in Fig. 5. In this figure, time runs from right to left as an aid to making comparisons with radiosonde, VHF wind profiler and RASP cross-sections presented later. Between about 2100 UTC 28 August (0630 LST) and 0500 UTC 29 August (1430 LST), the wind strengthened and backed from a north-easterly to a westerly as the cut-off low approached. Throughout this period the temperature increased from an overnight minimum of 8.5 °C to a local maximum of 13 °C just before the arrival of a weak cold front at about 0500 UTC, which was marked by a relative pressure minimum. Behind the cold front, the wind direction remained relatively steady from around 280–290°. The absolute minimum pressure at Buckland Park, 981 hPa, occurred at about 1830 UTC 29 August (0230 LST), and marked the passage of the secondary warm front. Prior to this, the wind had backed from a north-westerly to a westerly. Wind gusts exceeding 15 m s\(^{-1}\) were recorded around the time of the pressure minimum, and the heaviest rainfall was recorded shortly thereafter. The wind direction remained remarkably constant behind the warm front. With the passage of the warm front, the temperature rose from a minimum of about 8 °C at 1830 UTC 29 August (0230 LST) to nearly 15 °C at 0300 UTC 30 August (1230 LST). Significantly, this rapid increase in temperature took place in the early hours of the morning against the diurnal trend. For reference, the sun rose at 0628 LST and set at 1734 LST. Figure 5 shows also that when the secondary warm front passed through Buckland Park the wind shift and pressure trough were located near
Figure 4. Upper-level RASP analyses (see text) at 1100 UTC 29 August 1992. (a) System-relative winds on the 310 K isentropic surface and the height of the 310 K isentropic surface. Contour interval is 500 m. (b) Potential vorticity and system-relative winds on the 310 K isentropic surface. Contour interval is $5 \times 10^{-7}$ m$^2$ s$^{-1}$ K kg$^{-1}$.

For reference, the magnitude of the vector in the bottom left-hand corner of each frame is 45 m s$^{-1}$. 
Figure 5. Buckland Park automatic weather station data for 27–31 August 1992. (a) Mean-sea-level pressure (hPa) and temperature (°C), (b) wind speed (m s⁻¹), and (c) wind direction. Local midday is marked by vertical dashed lines. Note that time runs from right to left along the abscissa.
the temperature minimum. In contrast, the classical picture of a warm front has it on the warm side of the baroclinic zone.

According to Furler (1993), moderately heavy rain began to fall at Adelaide with the arrival of the cloud head at 1530 UTC 29 August. Four hours later a narrow convective band of heavy precipitation passed through Adelaide. The Bureau of Meteorology’s weather radar at Adelaide airport showed regions embedded within the convective band in which the precipitation exceeded 40 mm h\(^{-1}\). Strong surface winds exceeding 18 m s\(^{-1}\) and gusting to 25 m s\(^{-1}\) were recorded at Adelaide Airport with the passage of the convective line. Although the convective band intensified as it crossed the Mt. Lofty Ranges, Mills and Wu (1995) noted that the convective line developed south of Kangaroo Island (about 150 km southwest of Adelaide) some 6 hours earlier, and its remnants could still be identified in the GMS infrared satellite imagery at 2300 UTC 28 August (see Figs. 1(e) and 1(f), cloud band A). Many places around Adelaide received their highest August daily rainfall on record. For example, Lenswood, 20 km east of Adelaide, received 70 mm of rain between 1000 UTC and 2300 UTC 29 August, including 17 mm in one half-hour period to 1945 UTC (Furler 1993).

A mesoscale mean-sea-level pressure analysis for 0000 UTC 30 August based on the South Australian Regional Office’s analysis, the GMS infrared satellite image, and the surface records at Buckland Park is shown in Fig. 6. By this time the coldest air had already passed Adelaide. The pressure at the centre of the low, which lies to the south of
Adelaide, is 976 hPa. The weak cold front is analysed along the east coast with the wind changing from north-easterly ahead of the front to north-westerly behind, and the warm front extends south-eastward from the main low. The secondary warm front is oriented from the low towards the north-east, with a pronounced wind shift from northerlies to south-westerlies analysed across it. The analysis is consistent with the RASP mean-sea-level pressure and 900 hPa temperature analysis (Fig. 2(d)), and the infrared satellite imagery (Fig. 1(f)). However, the analysis is uncertain over the ocean because of the lack of observations there. Note that the strongest surface temperature gradients are associated with the secondary warm front.

(b) Meridional structure

Meridional cross-sections through 138°E at 1100 UTC 29 August from the RASP analysis are shown in Fig. 7. The dynamical tropopause is defined (in the southern hemisphere) as that region between −1 and −2 PV units, where a PV unit is 10⁻⁶ m²s⁻¹K kg⁻¹. The dynamical tropopause is blackened in each panel of Fig. 7. The cross-sections show a dramatic jump in the height of the tropopause at around 30°S. Equatorward of 30°S the tropopause height is greater than 15 km, plunges to about 4 km around 33°S, and rises to about 9 km by 45°S. Hoskins and Berrisford (1988) have discussed the structure of the intense storm that affected England in October 1987. While the storm examined by these authors was far more intense than that investigated here, both storms possessed comparable jumps in the tropopause height.

Contours of potential temperature in the meridional cross-section are depicted in Fig. 7(a). The concentration of isentropes at the surface near 23°S defines the subtropical front. This strong baroclinic region slopes poleward from around 23°S at the surface to around 33°S at the tropopause. A cold anomaly is located at the surface beneath the tropopause fold at about 35°S. Contours of equivalent potential temperature and relative humidity are plotted in Fig. 7(b). Two deep moist layers are analysed: the first slants poleward along the subtropical front and corresponds with the north-west cloud band (cloud band B in Fig. 1(e)); the second, to the south of the tropopause fold, marks the comma cloud on the poleward side of the cut-off low (cloud band C in Fig. 1(e)), and corresponds with the warm tongue. A pronounced cold, dry slot lies beneath the tropopause fold. The upper part of the dry slot is probably due to subsidence in the tropopause fold, while the lower part is related to the cold tongue (cf. the surface analysis at this time, Fig. 2(c)).

The meridional cross-section of zonal wind, Fig. 7(c), depicts a very strong westerly jet centred at around 30°S and at a height of 11 km with wind speeds exceeding 70 m s⁻¹ in the core. The strong westerlies on the equatorward side of the tropopause jump are part of the subtropical jet-stream, the lower section of which forms the upper-level jet evident in the 300 hPa height field (Fig. 3). Note also that at upper levels the flow changes from westerly on the equatorward side of the tropopause fold to easterly on its poleward side, reflecting the strong cyclonic circulation that must accompany such an intense cut-off low and deep tropopause fold. At lower levels, the change from westerlies to easterlies takes place further poleward, as the centre of the low-level circulation is south of the tropopause fold. A low-level maximum in the zonal wind is centred at 33°S and a height of about 1.5 km. This flow is relatively dry and corresponds with the cold tongue identified in Fig. 2(c). The warm tongue corresponds to the low-level easterly flow poleward of about 40°S.

(c) Time–height cross-section and zonal structure

Time–height cross-sections constructed from the radiosonde and wind-profiler observations, and zonal cross-sections from RASP at 34.35°S are now presented. Before
Figure 7. RASP analyses (see text) at 1100 UTC 29 August 1992. Meridional cross-section at 138.36°E of (a) potential temperature (K), (b) equivalent potential temperature (K) and (c) zonal wind (m s⁻¹). The region between potential vorticity PV = −1 and PV = −2 lines is blackened to show the dynamical tropopause. Contour intervals are 3 K for the potential temperatures and 5 m s⁻¹ for wind. The light and dark shaded regions show where the relative humidity is greater than 60% and 90% respectively. Dashed lines denote negative values.
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commencing this analysis, it is pertinent to comment on the differences between the cross-sections. Caution must be exercised when comparing time–height cross-sections (radiosondes and wind-profiler data) and the zonal cross-sections (RASP analyses); the cut-off low and subtropical front evolve throughout the analysis period, introducing a degree of ambiguity when making a time to space conversion. Despite this, the principal features can be identified in both types of cross-section.

The potential temperature measured by the radiosondes is shown in Fig. 8(a). The tropopause height, as determined by the radiosonde thermodynamic data, is marked for each flight by an ‘X’ or a ‘+’ depending respectively on whether the radiosonde was launched at Buckland Park or Adelaide Airport. In the warm air ahead of the system, the tropopause is raised to 12–14 km altitude, drops to 7 km above the cut-off low, and then rises again to about 10 km after the passage of the system. This intrusion of stratospheric air is a large-scale feature which is also analysed by RASP. A pronounced cold dome is evident at low levels at about 1400 UTC 29 August. The same characteristic pattern of the tropopause and isentropes was observed in a northern hemisphere cut-off low by Palmen (1949) and by numerous investigators since then. More recently, the same tropopause and isentrope pattern was noted in the theoretical study by Thorpe (1986), who investigated the thermal structure of a cross-section through an idealised cut-off low. Thorpe found that in the stratosphere the isentropes bulge downwards towards a lowered tropopause, and in the troposphere isentropes bend upwards towards and into the lowered stratosphere. The low-level structure is that of a cold-core cyclone, and is typical of a cut-off low before entering the warm-cored seclusion phase of its life cycle. The isentropes show distinct low-level warming with the passage of the cut-off low and tropopause fold.

Figure 8(b) shows the time–height cross-section of equivalent potential temperature constructed from the radiosonde data. The light and dark shaded areas indicate regions in
Figure 8. Time–height cross-section of (a) potential temperature, and (b) equivalent potential temperature. Contour interval is 3 K. The light and dark shaded regions show where the relative humidity is greater than 60% and 90% respectively. The thermal tropopause as determined by each radiosonde is marked by either an ‘X’ or a ‘+’ depending on whether the sonde was released at Buckland Park or Adelaide Airport. Note that time runs from right to left along the abscissa.
which the relative humidity is greater than 60% and 90% respectively. Relatively dry air is found well ahead of the surface low (before about 1400 UTC 28 August), followed by a deep moist layer, i.e. the warm tongue to the east of the surface low (cf. Fig. 2(a)). The leading edge of the warm tongue arrives at about 1400 UTC 28 August, and is marked by a distinct warm-frontal-like gradient in the equivalent potential temperature and humidity. Moreover, the equivalent potential temperature has a local maximum at around 1830 UTC 28 August at a height of 5 km. Conversely, the trailing edge of this warm tongue heralds a region of much drier and cooler air, i.e. the cold tongue, and coincides with the upper cold front and tropopause fold. Note the dry slot that accompanies the tropopause fold. From around 0200 UTC 29 August onwards, the air below 5 km is generally well mixed in equivalent potential temperature, with areas of potential instability beneath the tropopause fold. The sharp gradient in equivalent potential temperature at the trailing edge of the cold tongue (1900 UTC 29 August) marks the secondary warm front detected in the automatic weather station records (Fig. 5) and analysed in Fig. 6. This is followed by another broad region of potential instability late on 30 August.

Zonal cross-sections of potential temperature and equivalent potential temperature taken from the 1100 UTC 29 August RASP analysis are displayed in Figs. 9(a) and 9(b) respectively. Both figures show reasonable agreement with the time–height radiosonde cross-sections, especially in the region near the lowered tropopause (which is close to the time at which the cross-section is constructed). For example, the RASP zonal cross-section captures the deep moist layer in the warm air, the upper warm-frontal-like change, the deep tropopause fold, and the dry slot and cold tongue to the rear of the tropopause fold (cf. Figs. 8(b) and 9(b)). Note that RASP has analysed a stronger cold front at the surface (145°E) and a weaker warm front (124°E) than seen in the time–height sections.

The zonal and meridional wind components measured by the radiosondes are shown in Fig. 10. Throughout the period of observation, the zonal wind is predominantly westerly over Buckland Park. One of the most prominent features of the zonal wind field is the strong subtropical jet on the warm side of the tropopause fold (Fig. 10(a)). Wind speeds within the jet at 1500 UTC 28 August exceed 80 m s⁻¹ near 11 km altitude. Note the secondary zonal wind maximum within the tropopause fold itself, and the strong shear layers below both jets. The shear layer below the subtropical jet marks the top of the warm tongue which flows beneath the subtropical jet almost at right angles. Similarly, the cold tongue is capped by the shear layer at the base of the jet within the tropopause fold. The cloud head, which arrives at Adelaide at about 1530 UTC 29 August, is accompanied by 30 m s⁻¹ westerlies between about 2 and 3 km altitude. These features are reasonably consistent with the 1100 UTC 29 August RASP analysis (Fig. 11).

The cyclonic structure of the cut-off low is evident in the meridional wind field (Fig. 10(b)), with generally northerly flow ahead of the system and southerly flow behind. The northerly component of the subtropical jet can be seen at upper levels prior to the arrival of the tropopause fold. These northerlies extend downward into the middle troposphere marking the warm tongue. There is a region of particularly strong cyclonic shear at approximately 1200 UTC 29 August at 6 km altitude within the tropopause fold. Below the tropopause fold, between about 1200 UTC and 1900 UTC 29 August, there is a near-surface southerly jet accompanying the cloud head and warm front. Wind speeds within the jet exceed 10 m s⁻¹ at a height of 600 m. The winds accompanying the cloud head and warm front back with height, becoming strong and westerly between about 2 and 3 km altitude (see Fig. 10(a)). Such environments are favourable for organized convection.

Isotachs of the three-hourly averaged vertical velocity measured by the VHF wind profiler are plotted in Fig. 12. The three regions of apparent strong subsidence, centred around 2300 UTC 28 August, 1800 UTC 29 August and 0800 UTC 30 August at 2–3 km,
Figure 9. RASP analyses (see text) at 1100 UTC 29 August. Zonal cross-section at 34.35°S of (a) potential temperature (K) and (b) equivalent potential temperature (K). The region between potential vorticity PV = −1 and PV = −2 lines is blackened to show the dynamical tropopause. Contour intervals are 3 K. The light and dark shaded regions show where the relative humidity is greater than 60% and 90% respectively.
Figure 10. Time-height cross-section of (a) zonal wind (m s\(^{-1}\)) and (b) meridional wind (m s\(^{-1}\)) measured by the radiosondes. Contour intervals are 5 m s\(^{-1}\). Dashed lines denote negative values. The light and dark shaded regions show where the relative humidity is greater than 60% and 90% respectively. The thermal tropopause as determined by each radiosonde is marked by either an ‘X’ or a ‘+’ depending on whether the sonde was released at Buckland Park or Adelaide Airport. Note that time runs from right to left along the abscissa.
Figure 11. RASP analyses (see text) at 1100 UTC 29 August. Zonal cross-section at 34.35°S of (a) zonal wind (m s$^{-1}$) and (b) meridional wind (m s$^{-1}$). The region between potential vorticity PV = -1 and PV = -2 lines is blackened to show the dynamical tropopause. Contour intervals are 5 m s$^{-1}$. Dashed lines denote negative values. The light and dark shaded regions show where the relative humidity is greater than 60% and 90% respectively.
Figure 12. Time–height cross-section of vertical velocity (cm s\(^{-1}\)) as observed by the VHF profiler. The contour interval is 5 cm s\(^{-1}\). The light and dark shading indicates ascent and descent respectively. The thermal tropopause as determined by each radiosonde is marked by either an 'X' or a '+' depending on whether the sonde was released at Buckland Park or Adelaide Airport. Note that time runs from right to left along the abscissa.

are rain echoes due to hydrometeor contamination. Note that the first two regions of rain echo encompass the passage of the cold and warm fronts respectively. The remainder of Fig. 12 indicates air motion. Air subsides prior to about 0000 UTC 29 August, through the tropopause fold, and for most of the time from 0600 UTC 30 August onwards. There is a deep region of ascent in the warm air just ahead of the tropopause fold, and general ascent in a broad region below the fold. A comparison with the relative humidity (shaded on Fig. 10(b)) reveals ascent in moist regions and subsidence in drier regions. Although not shown here, the low-level vertical motion diagnosed from the RASP analyses is in broad agreement with that observed by the wind profiler. Note that the VHF wind profiler indicates ascent in the region of low-level warm advection to the west and north-east of the low (Fig. 2(d)). The warm-air advection is consistent with the observed ascent, and presumably initiated the intense convection in the very moist, unstable air mass following the passage of the tropopause fold. The pattern of vertical motion measured by the VHF wind profiler and plotted in Fig. 12 agrees well with the conceptual model of Hirschberg and Fritsch (1991).

5. Conclusions

High time-resolution radiosonde soundings, VHF wind-profiler retrievals, automatic weather station time series, and routine Australian Bureau of Meteorology RASP analyses have been combined to document the structure and evolution of an intense cut-off low
that passed to the south of Adelaide, Australia. Unfortunately, the routine observational network over virtually the entire southern hemisphere is only just adequate for detailed synoptic studies, and totally inadequate for investigations of mesoscale phenomena. For this reason, the vast majority of observational studies concerning extratropical cyclogenesis have been focussed on the northern hemisphere. As far as we know, this study is the most detailed of its kind to be concerned with the southern hemisphere.

The system documented here comprised two distinct components. The first was a subtropical jet with an associated north-west cloud band and subtropical surface front. This subtropical system extended south-eastwards across the central part of the continent. The second component was a cut-off low and associated upper-level PV anomaly, that developed poleward of the subtropical front over the ocean south of Australia. These two components interacted with each other while retaining their separate identities. The strongest temperature gradients were observed to lie through the subtropics, and were distinct from the midlatitude low pressure system. Throughout the period of observation, the subtropical temperature gradients strengthened while the midlatitude temperature gradients weakened. One of the conclusions from the study was that the Australian Bureau of Meteorology's 150 km resolution RASP analyses captured the broad-scale structure and evolution of the system reasonably well.

The system studied here was cold-core, and similar to the instant occlusion investigated by Browning and Hill (1985). In particular, the same dual-conveyor-belt pattern was observed. The major difference is that our system lay closer to the equator, the principal baroclinic region being the subtropical front.

Like the case of Browning and Hill (1985), our cut-off low produced a very deep tropopause fold. Over Adelaide, the tropopause descended to an altitude of about 5 km, and the temperature at 500 hPa fell to −30 °C. A very cold, potentially unstable air mass was observed below the fold. Meridional cross-sections, based on RASP analyses, showed that the tropopause height exceeded 15 km equatorward of 30°S, but fell sharply to about 4 km at around 33°S before rising to about 9 km by 45°S.

A strong warm front was observed at Buckland Park about 8 hours after the tropopause height minimum. The warm front defined the western edge of the cold dome, and was marked at surface by an absolute minimum in the pressure and temperature rise of about 7 °C. Significantly, this increase in temperature took place in the early hours of the morning against the diurnal trend. The system studied here produced very high rainfall, which resulted in flash flooding and much damage in the Adelaide Hills area. The most severe convection took place around the passage of the warm front in the region behind the lowered tropopause. The low-level warm-air advection, ascent, and strong low-level wind shear appeared to provide a favourable convective environment, particularly as the system approached the Adelaide Hills.

As already noted, the analyses showed strong low-level temperature gradients through central Australia in conjunction with the north-west cloud band. However, the association of the north-west cloud band with subtropical cold fronts had not been made explicit in previous studies. For example, Downey et al. (1981) observed a 'substantial thermal gradient over the Australian continent' but did not pursue this line of investigation. Bell (1982) did not identify the cloud band as being directly associated with a subtropical cold front, although in this case-study he analysed a front through central Australia and large-scale deformation suggesting frontogenesis. More recently, Smith et al. (1995) have documented the structure and evolution of subtropical fronts during late winter and early spring. Although not accompanied by such a well developed north-west cloud band, the subtropical cold fronts investigated by Smith et al. were associated with synoptic patterns and cut-off low developments similar to those presented here. Note that the maximum
frontogenetic activity is located through central Australia. This is similar to the observations taken by Smith et al. (1995) during the Central Australian Fronts Experiment.

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REFERENCES


Hinsch, P. A. and Fritsch, J. M. 1984 The ‘stretched delta’ cloud system—a satellite imaging precursor to major cyclogenesis in the eastern Australian—Western Tasman region. Weather and Forecasting, 10, 286-309


Palmen, E. 1949 Origin and structure of high level cyclones south of the maximum westerlies. *Tellus*, 1, 1–10


