DETAILED STRUCTURE OF TWO SUBTROPICAL FRONTAL ZONES

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Abstract: A study of special and routine data during the passage of two winter synoptic disturbances through the Woomera (lat. 31°S) area has revealed the following features.

A barotropic "trowal" is found at least in low levels, between two baroclinic zones, which may broadly be called, respectively, warm and cold frontal zones. The cold frontal zone is quite broad but embedded within it may be a concentrated line or lines of rapid change of temperature, wet bulb temperature or wind. The wind shear line does not necessarily occur at the "front" of strong density contrast, and changes in wind, temperature and wet bulb potential temperature in low levels may be masked at the surface by a low level inversion, so that "overrunning" of these changes may appear. The air mass boundary exhibits a different shape from that of the "front" as defined in terms of density contrast. It is affected by the middle level prefrontal cloud mass, which in turn is conditioned by ascending motions preceding (katafront) or both preceding and following (anafront) the surface frontal passage.

The low level jet is a nocturnal and morning phenomenon found approximately at the top of the low level inversion, and in the cases studied was topped by a layer of wind veering with height. The relation between change of wind direction with height and temperature advection is shown to be roughly as accounted for by inviscid theory except in the low levels during inversion conditions.

1. INTRODUCTION

Many investigations on cold fronts have been made by a number of Australian authors. Some of the deductions came from the accumulation of fragmentary evidence which can be obtained from data sources that include only once daily upper air soundings. Needless to say, these investigations suggest the difficulty of frontal analysis merely by surface observation and the importance of upper analysis has been emphasised.

* This investigation was carried out while studying at the C.S.I.R.O. Division of Meteorological Physics, Aspendale, Victoria.
The detailed analysis of cold fronts based on dense soundings was not possible until 1957 for "The summer cool change of South-Eastern Australia" by F. A. Berson, D. G. Reid and A. J. Troup (1957, 1959). Time cross-sections from radiosonde soundings at Aspendale with a time interval of four to six hours were shown there. A great deal of effort was devoted to the analysis of winds obtained by pilot balloons.

In the winter of 1963 the synoptic group headed by R. H. Clarke carried out observations at Woomera, with radio soundings every three hours and radar wind soundings every hour. Most of the soundings started well ahead of the passage of fronts and continued for half a day and sometimes a day. As far as surface observations are concerned, autographic records of temperature and pressure were available at stations shown in Fig. 1, in addition to visual cloud observation and routine observations at Woomera Meteorological Office (station 659 Fig. 2).

The Australian continent and the neighbouring oceans shown in Fig. 2 have sufficient weather observations to analyse surface maps, but the nearest island-station west of the Australian continent is Amsterdam Island, 2, 500 miles distant from Perth. The western and southwestern oceanic areas as far as the longitude of Amsterdam Island have surface ship observations, but the data coverage does not seem to be sufficient for investigating the life history of each synoptic system even on surface maps. Certainly, weather satellites have been providing cloud patterns once in a while. But it is still hard to deduce the synoptic pattern from cloud pictures, because of the difficulty that comes from the lack of a one to one correspondence between synoptic systems and cloud patterns.

So far as the upper observation network on the continent is concerned, nine radio sounding stations are located around the 30oS parallel and the average distance apart of these stations is 370 nautical miles. The farthest is 450 miles between Woomera and Cobar. Fig. 2 shows the network of upper sounding stations including those observing upper winds. The overall picture of synoptic patterns in three dimensions can be obtained, although the temperature field is sampled only once a day.

In this study most of the material is from the Woomera expedition. In order to obtain a broad view, space cross-sections and upper level charts were analysed in addition.

Concerning the concept of "front", Godske et al. (1957) described fronts as the lines of intersection of a surface of discontinuity with another surface. Discontinuities have horizontal gradients of air mass properties which are large as compared with the corresponding gradients within an air mass. The gradients which occur across fronts are defined to be between the limits

\[ 1^\circ C/10 \text{ km} < \frac{\partial T}{\partial n}, \frac{\partial \theta}{\partial n}, \frac{\partial \theta_w}{\partial n} < 1^\circ C/1 \text{ km}, \]

and for a zone of transition, or frontal zone,

\[ 1^\circ C/100 \text{ km} < \frac{\partial T}{\partial n}, \frac{\partial \theta}{\partial n}, \frac{\partial \theta_w}{\partial n} < 1^\circ C/10 \text{ km}, \]

where \( T, \theta, \theta_w \) are respectively temperature, potential temperature and wet bulb potential temperature and \( n \) is measured in the direction of the gradient.

In this paper, the magnitude of the gradients as a criterion has sometimes been disregarded. Importance was placed on the next two characteristics as pointed out by Boville (1956): a front should be "a reasonably continuous feature of the chart both in space and time". These notions require greater baroclinicity in the frontal layer than in the surrounding atmosphere.
Squall lines are supposed to be within an airmass, and cold air production by rain
associated with squall lines and thunderstorms is proposed by T. Fujita (1959). The front it-
self is considered to be composed of several lines of convective activity which are sometimes
referred to as mesoscale phenomena. The activity and number of lines depend in some way
upon the locality. The preferred region for this convective activity associated with a cold
front is the coastal region where cold air comes from the sea, such as the Japan Sea coast.
During winter, this area is under the influence of incessant shower activity forming lines, after
a cold outbreak there. The existence of cold air aloft is a good indicator of the convective
activity.

The supply of heat from the sea surface to the air of the lower layer is also important
for the occurrence of the convection. It was calculated by Manabe (1957) during the period
of a typical cold outbreak and found to be the predominant factor of the heat budget in the lower
half of the troposphere. When a front propagates to the inland region, where a continuous
supply of latent heat is cut off, the shower activity which accompanies a cold front or a line of
convective activity becomes weaker or disappears.

From the practical point of view, the distinction between a squall line and a front is
difficult enough and one simply regards the location of greater gradients as the front. Some
squall lines will not fulfil Godske's requirement concerning gradients. Many factors making
for the occurrence of strong gradients exist, especially in the lower layers. On the other hand,
a cold front is masked by cold air films under the surface inversion as is described by
Godske et al. (1957).

In relation to the masking of fronts, consideration is needed concerning the time of
routine weather observations in the analysis of surface data. Australia has three local standard
times called Eastern, Central, and Western Standard Times, which are based on the meridians
150°E, 142½°E and 120°E, respectively. The surface weather observations take place at
0900 local time for each region. But if one considers what is called the 2300Z map, for
example, surface data plotted on it are as shown in Fig. 2. It shows that the 0600 local time
observation is plotted in Western Australia, which corresponds to 2200Z. In the rest of
Australia, observations at 0900 local time are on the map. As the observations are not syn-
chronous, this causes difficulty in the analysis of the surface map, so that it seems that a
discontinuity of temperature lies at the border line of Western Australia with Northern Territory
and South Australia. As an example, Cook in South Australia has an observation time of
2330Z, which is 95 minutes after sunrise (middle of August), while a neighbouring station,
Forrest, observes at 2200Z, only 2 minutes after sunrise.

Another point to be noted is that no observation is made at 9 p.m. in Western Australia,
nor in the rest of Australia at midnight. Apart from this inconvenience for analysis, 2300Z is
the standard time of radio soundings, but a 2000Z release is used at Woomera during weekdays,
2300Z at weekends.

2. METHOD OF ANALYSIS

Among those properties Godske et al. took as criteria for the location of a front,
potential temperature is conservative in the course of dry adiabatic processes. Non-adiabatic
changes may be classified as due to the transfer of heat through diffusion, and radiative
processes. We also have potential temperature changes due to condensation or evaporation
processes. Smagorinsky (1960) proposes, for numerical prediction procedures, the use of the
formula

$$\frac{d \ln \theta}{dt} = \delta \frac{\Gamma}{p} \omega$$

where $\theta$, $t$, $p$, $\omega$ follow the usual notations, $\delta$ is the fraction of mass undergoing moist adia-
batic processes, and

$$\Gamma(T, p) = p \left( \frac{d \ln \theta}{dp} \right)_{\theta_E} = \text{const}$$
Fig. 1  Observing stations at Woomera. Topography is rather flat, with some mainly dry salt lakes.

Fig. 2  The aerological network, showing the line used for space sections and times of observations plotted on 23z surface map.
From this formula, the change of the overall pattern of potential temperature through ascent of moist air can be obtained. In the Australian region, especially at Woomera, this effect is frequently small because of dryness near the front, and the potential temperature of parcels may be considered to be substantially maintained except in the lower layers adjacent to the surface. Therefore, great emphasis is laid on isentropic patterns on upper cross-section charts. A case, however, has been studied, in which it is not possible to neglect the effect of condensation and evaporation, in order to explain even qualitatively the configuration of potential temperature.

Wet bulb potential temperature is conserved during moist adiabatic processes and this should be a better parameter for defining an airmass than potential temperature. But the effect of non-adiabatic processes, such as diurnal variation of heating and the supply of moisture from underlying layers through diffusion processes, also intrudes here. Moister air after the passage of a cold front is often observed, especially at stations not far from the ocean to the south or west. This characteristic appears distinctly when a front is weak. The criteria for the location of a front as a single line, such as that proposed by Reed (1958), is a convention which is not considered useful in an area of weak fronts.

Another way of locating the front is the arrival of a gust or a wind shift or a shower. These phenomena may not be simultaneous with other changes used as criteria for locating a front.

A property which is said to be potent for the identification of an airmass is mixing ratio. As long as no moisture is supplied or taken by the surroundings, and no condensation or evaporation takes place, this is also conservative. However, at Woomera, a clear-cut pattern of moisture is sometimes not obtained, and for this reason relative humidity is entered on the cross-sections, although this is not conservative.

With the development of satellite meteorology, interpretations of cloud pictures have been carried out in relation to synoptic features, especially those associated with a cut-off cyclone, by J.H. Conover (1962, 1963), R.E. Nagle and S.M. Serebreny (1962), and S. Fritz (1961). Most of these have investigated the cut-off or occluded low in the Northern Hemisphere. Useful rules for placing the cold front are summarised below, since some of the frontal systems seem to be associated with cut-off lows in the Australian region.

According to these investigations, a cold front is characteristically positioned under the solid cloud ahead of the clear or shower-free area and nearly parallel to the edge. This solid stratiform cloud band is bright on the cloud pictures. Unfortunately, TIROS pictures did not cover this area during the Woomera expedition. As a kind of substitute, average humidity for three layers, 1000 mb - 800 mb, 800 mb - 550 mb, and 550 mb - 300 mb, were taken into account as representing cloud amount for low, middle and high cloud, respectively, in accordance with Smagorinsky’s (1960) relationships.

To determine where to locate the front on the surface map is a difficult task, especially when the front is weak. The transition zone is so easy to find on the upper charts that 950, 900, 850, 800, 700 mb charts are constructed. The charts higher than 700 mb are thought not to show a distinct transition zone, as can be seen from the space cross-sections. The space cross-section is based on the soundings at stations along the line in Fig. 2. The data at widely spaced stations are supplemented by consulting upper charts already constructed. This cross-section provides an overall synoptic picture in spite of being only once a day. It also enables one to compare it with the time cross-section of upper soundings at Woomera.

A zone of wind shift without the character of a front is called a ‘shear line’ and is located at the place with maximum change of wind direction not only horizontally but vertically.

Although use of surface data is not recommended, a surface x-t diagram approximately along the line shown in Fig. 2 is made, locating the observations correctly in time.
3. THE DEGENERATING FRONT OF 18 TO 19 AUGUST 1963

A rather sharp front is located in Western Australia on the 18th, both on surface maps analysed by the Bureau of Meteorology, and on the x-t diagram, Fig. 3. This front has a temperature gradient of about 1°C/80 km, as judged from the routine network when it first appears. Although a rather large ascendant of dew point temperature is revealed roughly near the front, a dew point rise preceded the arrival of the front probably due to prefrontal rain. The wind shift from northwest to west was observed at the location of maximum temperature gradient during the 12 hours from 0700Z. In spite of the disappearance of the temperature gradient after 1600Z, a wind shear line can be traced from west to east as far as Woomera and the ascendant of dew point is fairly large at the passage of the shear line. The line decelerated from 40 knots to a mean of 29 knots after 2000Z. According to the autographic record at Woomera, the wind changes from NNW to WSW at 0730Z, 19 August, with a rise of humidity. There is no pressure jump at this time, but a general rise of pressure followed the minimum.

(a) The Surface and Upper Charts

Fig. 4a shows that high pressure centres are in the Tasman Sea, near Macquarie Island and Tennant Creek. A trough extends eastward from a low centre located at around 500 miles southwest of the southwestern tip of Western Australia. There seems to be the remnant of a low in this trough 400 miles south of Cook. From there, a shear line runs at first northeastward, then north-northwest, passing near Watson (station 650, Fig. 2). The surface temperature gradient usually associated with a cold front is not found across this line. But ahead of the line the area of combined middle cloud and upper cloud is conspicuous compared to the rear part of it, where cloud amount decreases and low cloud is observed.

The constant pressure charts show a very diffuse temperature transition zone. The maximum temperature gradient vector in the Woomera (659) - Forrest (646) area associated with the transition zone has been compared with the monthly mean component at the same place in the direction of this vector to demonstrate the existence of this zone. The result is shown in Table 1.

Table 1 - Temperature gradient in transition zone at 2300Z, 18/8/63, (°C/100 n. miles)

<table>
<thead>
<tr>
<th>Pressure Time</th>
<th>900</th>
<th>850</th>
<th>800</th>
<th>700</th>
</tr>
</thead>
<tbody>
<tr>
<td>2300Z</td>
<td>2.6</td>
<td>1.6</td>
<td>1.4</td>
<td>0.9</td>
</tr>
<tr>
<td>Average</td>
<td>0.7</td>
<td>1.0</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>

The transition zone is shown to be very shallow. At 700 mb the magnitude is equal to the monthly average, and the vector of the gradient deviates 90 degrees counterclockwise from the layers below. This means the thermal ridge abruptly tilts to the west between the layer of 800 mb and 700 mb. The level where the transition zone is easily found is 900 mb, which lies as shown in Fig. 4c. The 950 mb map shows the transition zone a little behind the 900 mb, but this level is within the low level inversion. The top of the inversion for some stations is listed in Table 2.

Table 2 - The pressure at the top of the inversion at 2300Z, 18/8/63

<table>
<thead>
<tr>
<th>Station</th>
<th>Giles (461)</th>
<th>Kalgoorlie (637)</th>
<th>Forrest (646)</th>
<th>Watson (650)</th>
<th>Woomera (659)</th>
<th>Adelaide (672)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station Pressure (mb)</td>
<td>923</td>
<td>958</td>
<td>950</td>
<td>950</td>
<td>940 (0014Z)</td>
<td>962</td>
</tr>
</tbody>
</table>

From this table the isotherm pattern at 950 mb is found to be somewhat influenced by the inversion and this level is not suitable for the purpose of locating the transition zone. The shear line which is found between Watson and Tarcoola (30° 42'S, 134° 33'E) extends upwards to 7000 ft at Watson at 2100Z. Correspondence of the shear line and transition zone is noted on the 900 mb map, but the exact location of either cannot be exactly designated from the upper charts.
Fig. 3  X–t diagram, showing surface data for 18–19 August 1963 along the line of Fig. 2.

- Shear line.
- Temperature.
- Dew point.
Fig. 4  Synoptic Charts for 23z 18th August, 1963.
The relative humidity pattern on each upper chart shows that the dry tongue is closely associated with the warm tongue up to 800 mb, with a steep ascendant of relative humidity along the shear line. A similar feature on the surface has already been described. But from 800-700 mb quite a contrast is seen as the thermal ridge tilts westward. The dry tongue in the lower layer is replaced by a moist tongue in the middle layer. This feature is conspicuously demonstrated not only on the space cross-section (Fig. 5) but on the time cross-section (Fig. 6) at Woomera.

The pattern of isentropes and moisture in Fig. 5 is similar to that of Fig. 6, if we suppose the movement of the system is about 20 knots eastward. There is a marked stable layer at 700 mb at Forrest (646) and a weak baroclinic transition zone east of Watson (650). The shear line is entered as the boundary between northerly wind ahead and westerly behind. A downward bulge in the isentropes is traceable near Watson from about 400 mb to 720 mb. Ahead of the shear line the low humidity in the lower layer up to 800 mb is topped by much higher values, with a strong decrease over the shear line. M.K. Miles (1962) mentions the rear edge of a pre-cold front cloud mass and found a large humidity gradient at 650 mb. He traced the warm dry air back to a cold source. The increase of moisture in the low layers is pronounced behind the shear line.

The time cross-section at Woomera

At 0019Z on the 19th a stable layer between 665 mb and 630 mb is topped by a deep humid layer and may erroneously be interpreted as a warm front. At 0305Z, the stable layer lies higher (620-610 mb), while a similar layer (645-615 mb) appears at 0552Z. The downward bulge of isentropes at around 0530Z in the layer between 400 mb and 900 mb is quite similar to what the Canadians call a trowal. R.J. Reed (1958) noted the same pattern on the vertical section from Northern Alaska to Inner Canada in his study of well defined cold frontal situations.

A stable layer including an inversion between 742 and 672 mb at 0910Z, may be interpreted as a frontal zone which accompanies the surface wind shift at 0730Z and which evinces a temperature gradient between 0552 and 0912Z of about 1°C/50 km in the layers below 700 mb. The layer below 742 mb shows a nearly moist adiabatic lapse rate. The rear edge of the middle cloud mass is about 2 hours ahead of the surface wind shift.

The pattern of wet bulb potential temperature shows some indication of change at around the passage of the surface wind shift, but the gradient is weak. Certainly, relatively warm moist air is found roughly from 0030Z to 0730Z, and cold dry air afterwards. However, the pattern below 950 mb in the former period is affected strongly by diurnal heating. The "overrunning" part of the low wet bulb potential temperature in the middle layer after 0730Z is brought about by the great reduction of relative humidity behind the edge of the middle cloud.

Wind structure in the vicinity of the shear line

The low level jet of maximum wind reaching 40 knots (Fig. 7) disappears at about 0300Z with the dissipation of the low level inversion. Pressure at the top of the inversion and the level of the maximum wind are listed in Table 3.

Table 3 - Pressure at the inversion top, and the level and velocity of maximum wind

<table>
<thead>
<tr>
<th>Time (Z)</th>
<th>0014Z</th>
<th>0105Z</th>
<th>0200Z</th>
<th>0305Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>940</td>
<td>-</td>
<td>-</td>
<td>912</td>
</tr>
<tr>
<td>The level of Max. Wind</td>
<td>940</td>
<td>935</td>
<td>920</td>
<td>920</td>
</tr>
<tr>
<td>Wind (kt/deg)</td>
<td>46/3450</td>
<td>34/3390</td>
<td>41/3340</td>
<td>32/3390</td>
</tr>
</tbody>
</table>
Fig. 5  Vertical Space Section along the line in Fig. 2
23z 18th August, 1963. Isentropes — Isohumes — Shear line •••

Fig. 6  Time Section at Woomera 20z to 20z, 18th-19th August, 1963.
Isohumes — Isentropes —
Wet-bulb Potential Temperature ——
Fig. 7  Time Section at Woomera 18th-19th Aug. 1963

Isotachs ——— Shear Line ·······

Layer in which wind veers with height ———

Fig. 8  Vertical space section at 23z 19th Aug. 1963. From Guildford (610) to Watson (650).

Fig. 9  Time section at Guildford, 19th-20th Aug. 1963

Isentropes ——— Isohumes ———

Wet-bulb Potential Temperature ———
This shows the top of the inversion almost coincides with the level of maximum wind in low levels as was described by Blackadar (1957), although the wind in the table is averaged over about 1000 ft. The wind shows general backing* with height until the passage of the shear line, but a shallow film of air with wind veering* with height is indicated in the figure. This is presumably due to turbulent processes above the inversion. Thirty-six minutes after the surface wind shift the wind has veered with height up to 730 mb, approximately the level of the inversion on the temperature sounding at 0910Z, marking the lower limit of the frontal zone. If this level is accepted as the depth of the cold air at 0806Z which began to arrive at the surface with the wind shift at 0730Z, the implied mean slope of the frontal zone is about 1:7 over a depth of about 8000 ft, and no further increase in depth takes place after about the first half hour.

Change of wind direction with time is very sharp at the surface and at 950 mb, but is gradual at higher levels, showing a prefrontal veering of 20 degrees at 900-800 mb some 2-3 hours before the surface wind shift and little change above this layer.

4. THE ACTIVE FRONT OF 21 AUGUST 1963

Figures 8 and 9 show the baroclinic transition zone on the day before it arrived at Woomera. Surface wind at Kalgoorlie (Station 637) backs from northwest to west at 0100Z, 20 August, with the initiation of rain and veers to northwest three hours later. At the time of this temporary change, experienced at Guildford (610) six hours earlier, the transition zone is located at both stations between 800 and 850 mb. It is difficult to locate a transition zone or front near ground level. A shear line is embedded in the transition zone. The pattern of wet bulb potential temperature gives some indication of air mass discontinuity in the transition zone, and bears some resemblance to Newton's (1959) time cross-section through a squall line.

Figure 10, the surface x-t diagram along the line of Figure 2, shows the concentrated temperature gradient in the same location as the large ascendant of dew point, in Western Australia. The marked wind shift from north to southwest came later, the distance behind the maximum gradients being estimated to be 300 miles, in contrast to the case of 19 August. The close association of concentrated temperature gradient with moisture ascendant is destroyed after the line passes Tarcoola. The zone of pronounced temperature gradient is apparently affected by heating during the day, which destroys the low level inversion. The marked moisture ascendant is traceable at least to Broken Hill (31º 58'S 141º 27'E), and the greatest temperature gradient is estimated to be 1°C/40 km from Figure 10.

According to the autographic record at Woomera, the wind shift from NW to W came at 0100Z (21st) simultaneously with a sharp rise of humidity and a temperature rise. A more marked increase of humidity came at about 0500Z, with a rise of 33 per cent in 10 minutes. The sharp drop of temperature occurred at the same time as the change of humidity, the magnitude being 10°F within 10 minutes. No change of wind direction is recorded, but the maximum gust of 42 knots came with the temperature fall and accompanying showers, which recorded .01 inch of rain. Three of the stations in Fig. 1 recorded a pressure jump, the amplitude and time of the rise being shown in Table 4.

* Footnote: The term "veering" is used in the sense of the Meteorological Office "Meteorological Glossary" to mean clockwise rotation, "backing" anticlockwise. This definition has the merit of universality.

<table>
<thead>
<tr>
<th>Station</th>
<th>Station A</th>
<th>Station B</th>
<th>Station C</th>
<th>Station D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>-</td>
<td>1.5 mb</td>
<td>1.2 mb</td>
<td>1 mb</td>
</tr>
<tr>
<td>Time (Z)</td>
<td>0540</td>
<td>0520</td>
<td>0515</td>
<td>0430</td>
</tr>
</tbody>
</table>
Fig. 10 X- diagram showing surface data for 20-21 August.

--- Line of strong dew-point ascendant.
--- Temperature  Dew point.
From the data the orientation and speed of the pressure jump line is approximately 325° and 15 knots. Surface wind veered to northwest afterwards and a sharp wind shift to southwest came at about 0930Z, with no pronounced change of temperature, humidity or pressure.

The Surface and Upper Charts

Fig. 11a shows a rather developed depression in the Bight, the centre being 400 miles south of Ceduna (653) with a cold front north-northeast, turning to north-northwest, reaching near Giles. The cloud pattern ahead and behind is similar to that of the 19th. The low level inversion is not persistent in the area near the front, which can readily be located. As in the foregoing case, the comparison of the temperature gradient with the monthly average normal to the transition zone is listed in Table 5.

Table 5. Temperature gradient in the transition zone
(°C/100 n. miles)

<table>
<thead>
<tr>
<th>Pressure Date</th>
<th>900</th>
<th>850</th>
<th>800</th>
<th>700</th>
</tr>
</thead>
<tbody>
<tr>
<td>2300Z</td>
<td>5.0</td>
<td>3.8</td>
<td>3.8</td>
<td>4.6</td>
</tr>
<tr>
<td>20 Aug.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monthly Average</td>
<td>1.0</td>
<td>1.0</td>
<td>0.6</td>
<td>0</td>
</tr>
</tbody>
</table>

The orientation of the transition zone is nearly meridional from 30°S to 38°S on Figs. 11b, c, d, e. The magnitude of the gradient is much greater than the monthly average, but does not meet the requirement of a front. Undoubtedly, it is impossible to obtain the locally concentrated temperature gradient from these maps. A better estimate can be made from the time section. The westward tilt of the transition zone is pronounced between 800mb and 700mb in accordance with the tilt of the thermal ridge ahead of the transition zone. In order to check local influences on the thermal pattern, the height of the low level inversion from some stations is listed in Table 6.

Table 6. Pressure at the inversion, 2300Z 20/9/63, (Woomera 0014Z, 21st)

<table>
<thead>
<tr>
<th>Station</th>
<th>Giles</th>
<th>Kalgoorlie</th>
<th>Forrest</th>
<th>Watson</th>
<th>Woomera</th>
<th>Adelaide</th>
<th>Cobar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station No.</td>
<td>461</td>
<td>637</td>
<td>646</td>
<td>650</td>
<td>659</td>
<td>672</td>
<td>701</td>
</tr>
<tr>
<td>Pressure</td>
<td>944</td>
<td>---------</td>
<td>No inversion</td>
<td>--------</td>
<td>956</td>
<td>958</td>
<td></td>
</tr>
</tbody>
</table>

The thermal pattern on the 950 mb chart is more representative than on 19th because the inversion is less in evidence.

The zone of sharp ascendant of relative humidity in the western half of South Australia, oriented NNW - SSE at 950 mb and 900 mb, agrees with the shear line and the baroclinic zone in the lower levels, but is lost at 850 and 800 mb in Western Australia although the baroclinic zone and shear line are still recognizable there. In Fig. 11f the temperature transition zone does not coincide with the zone of maximum humidity gradient and is less meridionally oriented. Fig. 12 shows a baroclinic zone, of which the leading part is associated with a shear line separating NW from W wind, and which reaches from 900 mb at Woomera to 700 mb at Watson. A sharp surface wind shift passed Woomera at 0100Z (Fig. 13) but in the layers 850 mb and 900 mb the wind shift is found near 2330Z, a feature observed in the first case. Watson's sounding showed a stable layer between 710 mb and 732 mb, which may be associated with an earlier baroclinic zone and shear line. The overall pattern of isentropes near Woomera in the lower and middle layers again recalls the Canadian trowal. The rear edge of the frontal cloud mass in this case is a little (50 miles, estimated from the time section) behind the surface position of the cold front.

The increasing humidity behind the cold front near the surface is remarkable, and Watson exhibits convectively unstable stratification.
Fig. II Synoptic Charts for 23z 20th August, 1963.
Fig. 12 Vertical Space Section at 23z 20th August, 1963.
Isentropes —— Isohumes
Wet-bulb Potential Temperature

Fig. 13 Time Section at Woomera 20th-21st August, 1963.
Isentropes —— Isohumes
Wet-bulb Potential Temperature
On the time section (Fig. 13) two baroclinic zones appear, the first being gently sloped, the second steep with a surface temperature gradient measured by the thermograph of 0.9°C/km. The pressure at a stable layer associated with the baroclinic zone and the shear line is indicated in Table 7.

Table 7. Stable layer at Woomera on 21/8/63

<table>
<thead>
<tr>
<th>Time Item</th>
<th>02.43Z</th>
<th>04.10Z</th>
<th>05.53Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base (mb)</td>
<td>810</td>
<td>760</td>
<td>715</td>
</tr>
<tr>
<td>Top (mb)</td>
<td>790</td>
<td>735</td>
<td>670</td>
</tr>
</tbody>
</table>

A stable layer which is like a frontal one in the layer of 900 - 950 mb at 0019Z is considered to be the remnant of a nocturnal inversion. The cooling between 2000Z and 0019Z marks the first baroclinic zone which includes the stable layer in Table 7. This does not reach the ground but merges with the remnants of the nocturnal inversion. The humidity above this stable layer is high and this feature persists until 0553Z. After the disappearance of the low level inversion, a super-adiabatic layer appears by diurnal warming below the stable layer at 0243Z.

In the time section the pattern of wet bulb potential temperature shows a very steep zone of transition about 0530Z. In the low levels there is a suggestion of overrunning by the cold air mass. The discontinuity at 0500Z is accompanied by a pressure jump, rain and temperature change. It will be noted that two features, the cold front and a shear line accompanying an earlier baroclinic feature, can be identified on both the space (Fig. 12) and time (Fig. 13) sections.

The time section also shows a concentrated gradient of wet bulb potential temperature near 0925Z, mainly due to low humidity behind this zone. A stable layer from 765 to 600 mb at 0925Z represents the frontal zone, at the bottom of which a 1°C inversion is found as in the case of 19 August.

Wind structure (Fig. 14)

A low level jet of maximum wind 42 knots is found in the early morning (2140Z). Data are not available to reveal whether this lies at the top of the inversion. The marked wind shift at the surface, at about 0100Z, is confined to a thin layer and is presumably due to the disappearance of the low level inversion. The shear line aloft came earlier, associated with the baroclinic zone, and veering of wind with height is found in a deep layer reaching above 700mb. This implies cold advection except near the surface. The other jet in the middle layer is located on top of the first baroclinic zone (2330-0230Z), its maximum being at the top of the layer whose wind veers with height, and this feature can be traced in vestigial form right through to 1030Z, at the end of the series.

The shear line merges with the cold front at about 0600Z. An unexpected feature is the temporary low level backing of the wind behind the front. By 0939Z the veering with height at all levels is re-established to middle levels.

5. VERTICAL WIND STRUCTURE AND TEMPERATURE ADVECTION

Here we formulate the relationship between wind direction and temperature advection by modifying Forsyth's (1955) gradient wind equation by the addition of a stress term.

Then

\[ 2 \Omega \frac{\partial \phi}{\partial z} + VK_H \frac{\partial \psi}{\partial \phi} + \frac{\partial (VK_H)}{\partial \phi} \psi = - \frac{\nabla^2 T^*}{\nabla^2 T^* \times \kappa} + \frac{1}{\rho g} \frac{\partial^2 \phi}{\partial z^2} \times \kappa \quad \ldots (1) \]

where \( \Omega \), \( \psi \), \( V \), \( \nabla^2 T^* \), \( p \), \( g \), \( z \), \( \kappa \) have their usual meaning, \( \phi \) is geopotential, \( T \) is horizontal stress, \( K_H \) trajectory curvature projected horizontally, \( T^* \) is virtual temperature.
Fig. 14 Time Section at Woomera showing isotachs. 20th-21st Aug. 1963. Wind shift line.

Fig. 15 "Stream lines" at Woomera 18th-19th Aug. 1963.

Fig. 16 "Stream lines" at Woomera 20th-21st Aug. 1963.
Multiplying vectorially by \( \nabla \), we obtain
\[
2 \Omega_z \nabla \times \frac{\partial Y}{\partial z} + V K_H (Y \times \frac{\partial Y}{\partial z}) = \frac{Y \cdot \nabla \rho}{\rho_g} \frac{T^*}{T} - \frac{1}{\rho_g} \frac{\partial Y}{\partial z} \frac{T^*}{T} \frac{\partial Y}{\partial z} + \frac{k \cdot \nabla Y}{\rho_g} \frac{\partial^2 Y}{\partial z^2} \cdots (2)
\]

The vertical component of \( \nabla \times \frac{\partial Y}{\partial z} \) is \( (u \frac{\partial Y}{\partial z} - v \frac{\partial Y}{\partial z}) = v^2 \frac{\partial Y}{\partial z} \) where \( \alpha \) is horizontal wind direction, positive clockwise. For a horizontal wind the last two terms of Eq. (2) are zero and exclusion of the fourth term in Eq. (2) provides the following generalizations:

(a) Veering and backing of wind with height correspond to cold advection and warm advection, respectively, as long as the trajectory curvature is cyclonic;

(b) If the trajectory is anticyclonically curved, the same relationship holds so long as \( |2\Omega_z| > |VK_H| \).

In order to apply the formula (2) we transform the third term, assuming adiabatic processes and isobaric flow, thus:
\[
\frac{V \cdot \nabla \rho}{\rho_g} \frac{T^*}{T} \approx \frac{1}{\Theta} \frac{V \cdot \nabla \Theta}{\Theta} = -\frac{1}{\Theta} \frac{\partial \Theta}{\partial t}
\]

Near the discontinuities under study, the curvature of trajectories is cyclonic as was shown in Fig. 5 and Fig. 13, so the neglect of the second term in Eq. (2) does not change the sign of deduced thermal advection. The comparison of the first term with the third term is shown in Table 8.

Table 8. \( 2\Omega_z v^2 \frac{\partial \Theta}{\partial z} \) and thermal advection at Woomera, 19 August 1963

<table>
<thead>
<tr>
<th>Time (z)</th>
<th>Height (mb)</th>
<th>( 2\Omega_z v^2 \frac{\partial \Theta}{\partial z} \times 10^6 \text{ (sec}^{-1} )</th>
<th>( \frac{1}{\Theta} \frac{\partial \Theta}{\partial t} \times 10^6 \text{ (sec}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0255</td>
<td>920</td>
<td>-1.9</td>
<td>0</td>
</tr>
<tr>
<td>880</td>
<td>-1.1</td>
<td>-0.1</td>
<td>-0.25</td>
</tr>
<tr>
<td>840</td>
<td>-0.1</td>
<td>-0.1</td>
<td>-0.25</td>
</tr>
<tr>
<td>800</td>
<td>0</td>
<td>-0.25</td>
<td>-0.35</td>
</tr>
<tr>
<td>770</td>
<td>-0.25</td>
<td>-0.35</td>
<td>-0.35</td>
</tr>
<tr>
<td>730</td>
<td>-0.35</td>
<td>-0.35</td>
<td>-0.35</td>
</tr>
<tr>
<td>700</td>
<td>-0.8</td>
<td>-0.8</td>
<td>-0.5</td>
</tr>
<tr>
<td>680</td>
<td>-0.55</td>
<td>-0.5</td>
<td>-0.25</td>
</tr>
<tr>
<td>0614</td>
<td>920</td>
<td>-0.35</td>
<td>0</td>
</tr>
<tr>
<td>880</td>
<td>-0.6</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>845</td>
<td>0.1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>810</td>
<td>0.45</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>770</td>
<td>0.3</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>740</td>
<td>0.15</td>
<td>0.45</td>
<td>0.25</td>
</tr>
<tr>
<td>705</td>
<td>0</td>
<td>0.25</td>
<td>0</td>
</tr>
<tr>
<td>675</td>
<td>-0.1</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>0900</td>
<td>920</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>900</td>
<td>0.1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>875</td>
<td>0.2</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>825</td>
<td>0.4</td>
<td>0.65</td>
<td>0.7</td>
</tr>
<tr>
<td>790</td>
<td>0.4</td>
<td>0.75</td>
<td>0.7</td>
</tr>
<tr>
<td>760</td>
<td>0</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>725</td>
<td>-0.2</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>695</td>
<td>-0.75</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Although the assessment is necessarily crude, on the whole rather good agreement is obtained apart from the lower layers. A large discrepancy is noted in the lowest levels of the first example. At this time the low level inversion lies between 950 mb and 925 mb. The low level inversion does not occur in the latter two cases. This suggests that the effect of shearing stress on the wind is greater when the low level inversion exists. The shearing stress term was estimated by taking the value of the Austausch coefficient 10 gm cm$^{-1}$ sec$^{-1}$ which was obtained by Taylor (1915). It amounts to $0.8 \times 10^{-6}$ sec$^{-1}$ at 880 mb at 0255Z, which tends to redress the discrepancy.

It is concluded from these examples that direction change of wind with height has a close relation to thermal advection, except for the lower layers affected by surface friction. A low level inversion, if it exists, contributes more to the discrepancy in the lower layers.

6. DISCUSSION AND SUMMARY

Marked barotropy is confined to the tropics, which is narrow compared with the baroclinic part. In the situations studied, baroclinicity is generally in evidence. Three kinds of sharp change associated with well developed baroclinicity are as follows:

(i) Shear lines with a marked change of wind direction;
(ii) Fronts and frontal zones in which horizontal density gradients are pronounced;
(iii) An air mass boundary distinguishable by total heat content, as measured by wet bulb potential temperature.

In the area under study, cold air comes from the ocean, and is moist in low levels. This tends to reduce the contrast in wet bulb potential temperature across air mass boundaries.

The rear edge of the middle cloud band marks a sharp decrease in humidity and wet bulb potential temperature, which suggests a kind of air mass boundary even above the maximum level reached by the front. This distinction between air mass boundary and front has been commented on by Wallington (1962).

Local convectivity may of course result in non-representative data, especially in prefrontal flights.

The wind shear line is a continuous entity in place and time, especially in the layer below 950 mb, but becomes more diffuse aloft, where veering is observed to occur earlier than at the surface in the 900-800 mb layers. It is found in association with frontal zones, but the most intense front has no such feature.

The air mass boundary in the cases studied is rather broad, and in low levels is affected by heat and moisture exchange with the surface.

The rear edge of the middle cloud mass marks the cessation of ascending motion (for a discussion of this technique see Clarke, 1961) as is shown for 19 August by the "stream lines" of Fig. 15. Upward motion is shown in the middle cloud mass of prefrontal and frontal zones. On 21 August, the relative position of the edge of the middle cloud mass and the surface cold front is different from the 19th, in that the middle cloud mass extends above the cold front. This finding agrees well with that of satellite cloud studies. The first case shows the dry zone found above the front by Sawyer (1955). If one applies the frontal classification of Bergeron (1937) used by Sansom (1950), the fronts of 19 and 21 August could be called respectively a kata- and an ana-front. The more complicated pattern (Fig. 16) behind the front on 21 August suggests that the cold air may have arrived in three discrete bursts.
The analysis of surface data was considered to be unsatisfactory for the study of cold fronts; however, the sharp ascendant of dew point temperature on the x-t diagram was found to be a useful indicator of frontal passage and this is found broadly true also of shear lines.

ACKNOWLEDGEMENTS

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REFERENCES

Bergeron, T. 
Bjerknes, J. and Bundgaard, R. C.
<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Publication/Book Title</th>
</tr>
</thead>
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