Aust. Met. Mag. 34 (1986) 65-76 551.515.8

Several atmospheric bores and a cold front over southern Australia

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(Manuscript received January 1986; revised June 1986)

Available data have been collected concerning several events which appear to have been internal atmospheric bores over southern Australia. Two photographs are shown, one of a probable inland winter bore, the other of a summer bore over the sea. Data to hand suggest that internal atmospheric bores are commonly activated by gravity currents, and that at least initially, their propagation speed approximates that of the gravity current.

The cold front accompanying the summertime bore is examined in as much detail as possible. It is found to have a very marked vortex structure near its leading edge, the wind behind the vortex being considerably less than the speed of propagation. The front assumed a bore-like character, including undulations, during its passage over the sea in the vicinity of Kangaroo Island, but reverted to being an unsteady gravity current on regaining the heated mainland, as shown by the rapid surface-cooling. The probability of such a dual character is indicated by recent laboratory experiments.

Introduction

Internal atmospheric bores have been investigated over northern Australia (see e.g. Clarke et al. 1981; Smith et al. 1982; Clarke 1983; Smith and Morton 1984; Clarke 1984; Crook and Miller 1985; Smith, Coughlan and Evans-Lopez 1986) and are now better understood. They are marked by a typical surface pressure signature (a jump, often followed by waves), one or more roll clouds when the low level air is moist enough, and a wind change to a direction nearly normal to the bore. They can only occur when the pre-bore atmosphere is stratified in low levels (e.g. to a few hundred metres) and nearly neutral above.

A bore, as a wave, is distinguished from a gravity current by the fact that (a) flow relative to the disturbance can be everywhere negative (i.e. forward velocity is everywhere less than that of the bore), although cases of small closed circulations near the leading edge of bores are not unknown (Davis and Acrivos 1967; Christie et al. 1978; Clarke et al. 1981; Crook and Miller 1985), and (b) cooling just behind the leading edge is the result of vertical rather than horizontal advection, and hence there is no cooling at the surface, as in the case of gravity currents.

It should be noted that the two-fluid experiments of Wood and Simpson (1984) exemplify the case of steady-state gravity currents of supercritical velocity (i.e. the current is faster than the propagation rate of small amplitude waves in the invaded medium). They show that if the invaded medium has only a shallow dense layer, the behaviour of the surge is similar to that of a gravity current moving into an unstratified environment. In this case, turbulence occurs behind the friction head of the gravity current. With a more deeply stratified invaded medium there is no turbulence behind the friction head, and the behaviour is that of an undular bore rather than of a gravity current. Thus one type of phenomenon merges into the other as the stratification of the invaded medium is changed.

The case of a subcritical gravity current, where the speed of small amplitude waves in the environment is greater than that of the current, has been treated by Crook and Miller (1985). In this case the gravity current is left behind, and an undular bore, with waves which (in the realistic case) evanesce in the horizontal (i.e. are limited in number), moves out ahead of it, like the morning glory (Clarke 1984). In the morning glory sequence the gravity current rapidly loses its identity, and the bore, moving at almost the same speed as the erstwhile gravity current, replaces it as the noteworthy event.

It is well known, from the work of Christie et al. (1978, 1979) that a bore tends to decay with time into a train of parallel finite amplitude solitary waves, and that these can pose a hazard to low-flying aircraft (Christie and Muirhead 1983a, 1983b).

Events resembling bores are occasionally reported over southern Australia (a referee suggests that roll clouds occur once or twice per year at a site near Adelaide) but details of their formation are invariably lacking. In this paper we shall examine briefly a few recent occurrences, and present an expanded description of one of them.

Some examples of probable southern Australian bores

Table 1 lists seven events which are thought to have been internal atmospheric bores.

Event 1 is described below in as much detail as possible. Event 2 is perhaps the best known, and was probably similar in origin to the events described by Shreffler and Binkowski (1981) and Haase and Smith (1984).

Event 3 has not been described in the literature. A roll cloud and ruffled sea surface were seen and photographed from a low-flying aircraft by a RAAF officer during an eastbound flight from Perth to Adelaide. The photograph is unsuitable for reproduction; it shows a line of cloud, perhaps 5 km long, but also a disturbance of the sea surface continuing without cloud far to the south, indicating a sharp wind change, the whole being oriented NNW-SSE. The photographer commented in his brief letter: 'There was a vast wind shear, veering 150 degrees in direction, and increasing in speed by 10 m s^{-1}, with a sharp turbulent period lasting about 30 seconds'. This suggests a width of about 4 km. From the synoptic chart and other records, it seems almost certain that this line coincided with a dry cold front which passed Esperance (E in Fig. 7) at about 0130, with a very sharp surface wind change from north-northwest to southwest. It may well have had a bore-like character, like Event 1. The disturbance was moving east at about 16 m $s^{-1}$when observed, but decelerated to only 10 m s^{-1} on the following day.

In Event 4 there was no cloud. Several solitary waves are described by Drake, near Yorke Peninsula, SA, in the early morning (local time). What was evidently an undular bore was marked by insects and supported by a spectacular anemogram, showing marked oscillations with a period of about 8 min. A strong presumption exists that the impetus for this phenomenon came from a cold front, which on the previous day was moving towards Spencer Gulf. This author has traced the disturbance, oriented northwest-southeast and moving towards northeast at 9 m s^{-1}, from Ceduna to Adelaide (see Fig. 3 for locations). At both places the anemogram showed a temporary (about 30-min duration) backing of the wind from north to southwest and minor pressure jumps were recorded at Neptune Island, Çape Borda, Cape Willoughby and Adelaide.

Table 1. Probable bores over southern Australia.

Event No	Date	Time*	Place	Lat. Long.	Evidence	Probable origin	Orientation	Reported by
1	17/1/69	0300	Pondalowie Bay, SA	35°S 137°E	Roll cloud Pressure jump Waves	Cold front	NNW-SSE	P.E. Geytenbeek (private communication)
2	27/11/77	0345	near Port Lincoln, SA	35°S 136°E	Double roll cloud	Thunderstorm outflow	N-S (?)	A. G. Robin (1978)
3	12/2/81	0800	Geat Aust. Bight.	33°S 129°E	Roll cloud Strong shear	Cold front	NNW-SSE	F/Lt E. J. Mannings (private communication)
4	17/9/81	1630	Yorke Peninsula, SA	35°S 137°E	Insects seen by radar	Cold front	NW-SE	V. A. Drake (1984)
5	6/1/84	2300	near Port Phillip Bay, Victoria	38°S 145°E	Series of roll clouds Pressure jump	Cold front	NW-SE	D. T. Mulroney (1984) W. L. Physick (1986)
6	31/1/85	0830	near Perth, WA	32°S 116°E	Series of roll clouds Pressure jump	Thunderstorm outflow, interacting with sea breeze	E-W	A. J. Prata and L. van Bruegel (1986)
7	1/6/85	2025	Oodnadatta, SA	28°S 135°E	Roll cloud Wind gust Pressure jump	Cold front	WNW-ESE	R. Hoebee (private communication)

* All times are GMT unless otherwise specified.

Fig. 1(a) Receding roll cloud at Oodnadatta, South Australia, 2125 1 June 1985. (Photograph by Mrs R. Hoebee.)

An event evidently similar to Event 6 has been described by Smith (1986) in the vicinity of Port Hedland, WA.

Event 7 (see photograph, Fig. 1 (a)) was witnessed by the weather observer at Oodnadatta, SA (for location see Fig. 7). He described it as a 'morning glory-type event', 'a long line of stratus at 150 m, which passed over the station from south to north with a 9 m s^{-1} wind gust from southwest, then back to calm'. The cloud was estimated to be 20 km long and 1 km wide. The surface temperature was low (5 °C) compared with the maximum for the previous day (17 °C), and the 'lifted condensation level' derived from the surface data was 125 m. The anemogram is shown in Fig. 1 (b). A pressure jump of about ½ mb was recorded. No temperature soundings are available; the upper winds at 1745 and 2345 were both about 5 m s^{-1} from southwest up to 2000 m. The indications are that the event was a bore, very similar to that witnessed at Daly Waters (lat. 16°15′S, long. 133°22′E) at 2300 h on 31 July 1974, during the Koorin Expedition (Clarke and Brook (eds) 1979) and that it was activated by a cold front which passed Ceduna (see Fig. 3) at 0200. The front-bore system would require a speed of about 8 m s^{-1} to reach Oodnadatta at the observed time. See the Appendix for more details of the Daly Waters bore, the only case documented 'before and after' in Australia, apart from morning glories.

The roll cloud photographed at Pondalowie Bay

The location on Yorke Peninsula is shown in Fig. 3. The photograph (see Fig. 2) was taken at about 0300 h on 17 January 1969 by P. E. Geytenbeek, with whom the date has been definitely confirmed. A similar cloud was photographed by the Neptune Island lightkeeper 'in 1969', but the date remains uncertain. The Cape Borda observer reported 'roll cloud to the west at 0120' on 17 January. These observations suggest that the cloud line was at least 60 km long, but the pressure-jump line accompanying it was at least 800 km in length, as shown by the available autographic records and 'discontinuity reports'. Investigation of apparently similar 'roll clouds' on and near Cape York Peninsula in north Queensland have shown that they are long and thin (perhaps one or several kilometres wide and one kilometre deep), and often very

Fig. 1(b) Anemogram from Oodnadatta for portion of 1 June 1985, showing the record of the wind gust accompanying the roll cloud at 2125 h (1 kn = 0.514 m s^{-1}).

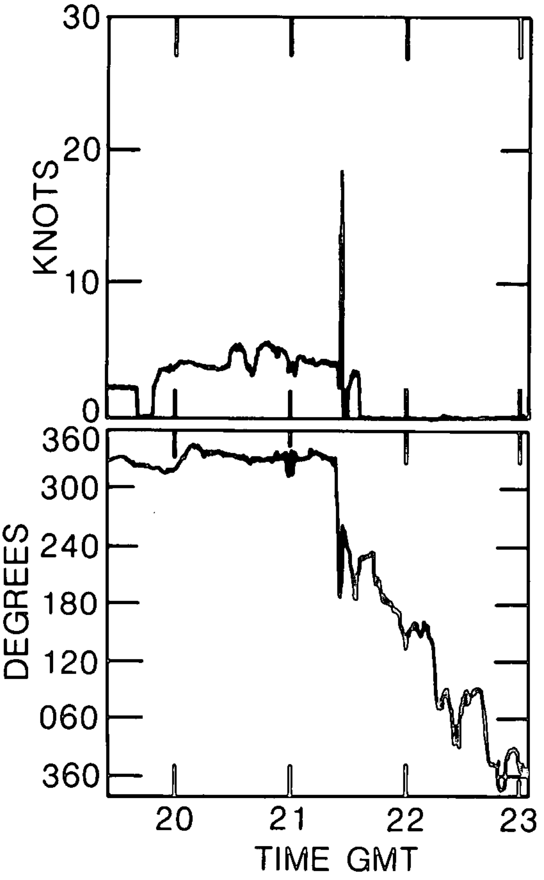
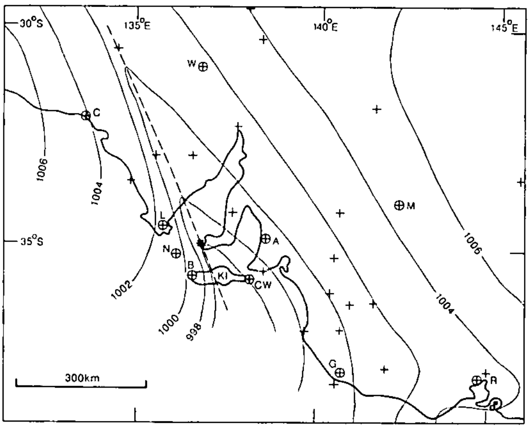


Fig. 3. Chart for 0200 17 January 1969, showing isobars, trough line and places mentioned in the text. + indicates a synoptic observation at 0200; o a barogram with a pressure jump; C, Ceduna; L, Port Lincoln; N, Neptune Island; B, Cape Borda; CW, Cape Willoughby; A, Adelaide; G, Mount Gambier; M, Mildura; R, Royal Australian Air Force Base at Laverton, Vic; KI, Kangaroo Island; *, Pondalowie Bay.



smooth, although second and subsequent lines, when they occur, tend to exhibit convective elements, suggestive of turbulence. The typical roll cloud is accompanied by a pressure jump and a wind squall blowing towards the direction of propagation. Time-lapse movies have shown ascent in front, of the order of several metres per second, and descent in the rear.

The height of the cliff in Fig. 2 is about 30 m, and the 'lifted condensation level' of the surface air at Neptune Island before the passage of the disturbance was 140 m. The cliff is just 1 km west-southwest of the photographer, while the marine horizon is about 6 km distant. These data suggest that the top of the

Fig. 2. Roll cloud 0300 17 January 1969. Looking west-southwest towards approaching cloud from Pondalowie Bay, Yorke Peninsula, South Australia. (Photograph by P. E. Geytenbeek.)

roll cloud was about 500 m above sea level. Its resemblance to the leading roll in a north Queensland morning glory is striking, although its scale may be diminished. The orientation (NNW-SSE) is that of the synoptic cold frontal trough accompanying the roll cloud (see Fig. 3).

No cloud other than the roll was reported anywhere within the map area of Fig. 3. Inland temperatures ranged from 35-40 °C ahead of the sharp frontal trough, while behind it, in coastal areas, they were about 22 °C. Sharp wind changes were reported from Ceduna (0045), Adelaide (0500), Port Lincoln (0133), Mount Gambier (0625), Cape Borda (0130) and several other places with subjective reports (not shown on the synoptic map). The strongest gusts were in the northerly winds preceding the change, and were up to 25 m s^{-1} at stations with anemographs. From the times of arrival of the wind change it is possible to determine the speed and orientation of the change line. This was done by least squares fitting to the hypothesis of a straight line disturbance with constant speed, using seven observations of time of passage. The result was an orientation of 342-162 degrees and a speed of 17½ m s^{-1}, considered to be correct to within 0.5 m s^{-1}, in the Port Lincoln-Adelaide area.

The Adelaide (city) anemogram is shown in Fig. 4 (a). This has been used to estimate the probable wind at its level of maximum, most likely at a height of about 300 m, by assuming that the maximum gust in each 5-minute interval represents the wind at the level of maximum. The wind thus estimated has been resolved into components u_{max}, normal to the wind change line and positive in its direction of motion, and v_{max}, in a direction parallel to the front, turned anticlockwise by a right angle from the direction of motion. The figure (4(b)) clearly suggests that wind normal to the front was in excess of its translation speed only for a distance behind the front of 10 to 20 km.

Fig. 4(a) Anemogram from Adelaide Bureau of Meteorology for portion of 17 January 1969. The time is local (GMT + 9½ h), and the windspeed is in knots (1 kn = 0.514 m s^{-1}).

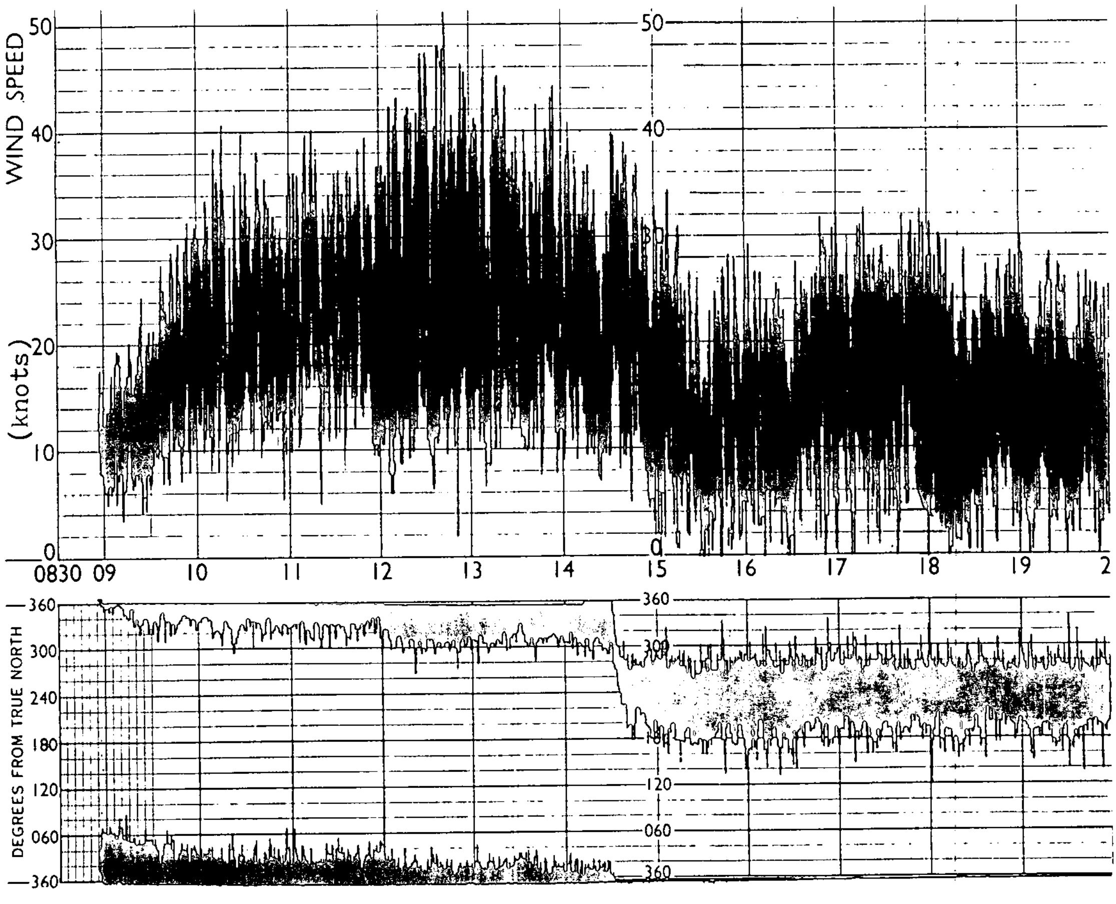
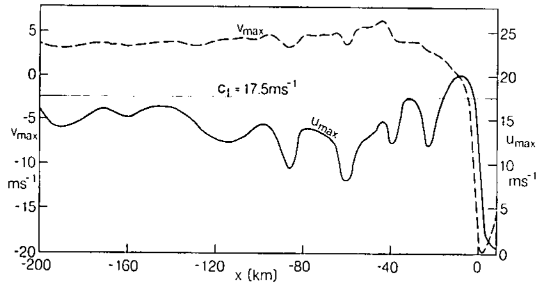


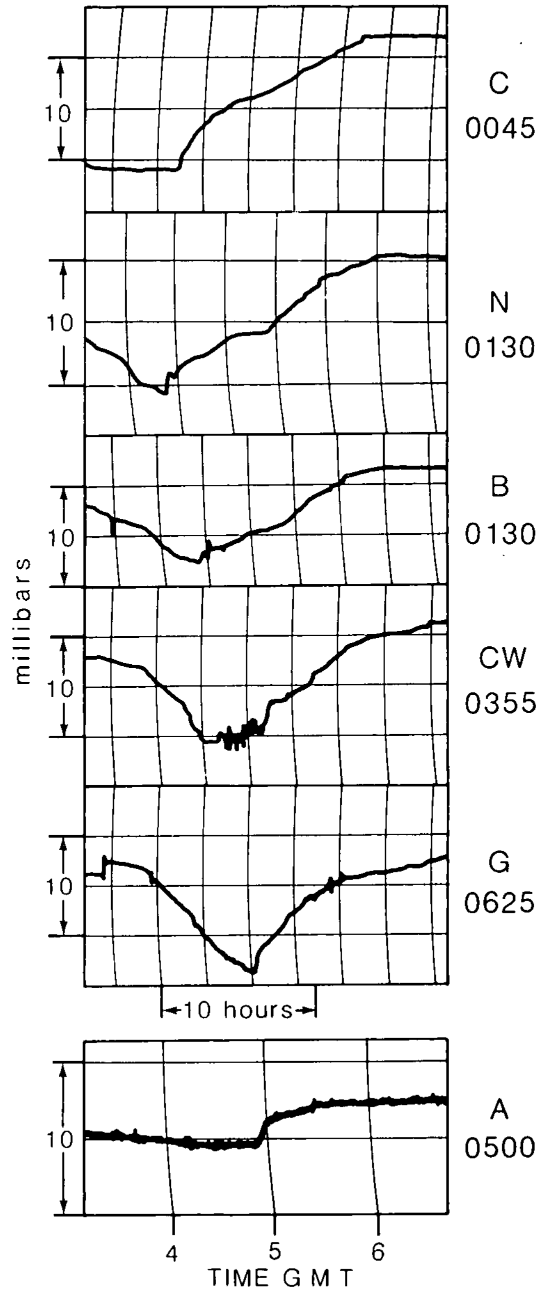
Fig. 4(b) Estimated wind component normal to the front (u_{max}) and the component parallel to it (v_{max}) obtained from the anemogram by assuming that the maximum gust in each 5-min interval indicates the maximum wind speed in the vertical at a height of a few hundred metres. The speed c_f of the front is also shown for comparison. Space variation has been substituted for time by translating the front at $17\frac{1}{2}$ m s^{-1}.



Weekly barograms for several stations and a daily one for Adelaide are displayed in Fig. 5. The pressure changes with the passage of the trough and front are abrupt increases of 1-2 mb (over a period of 4-5 minutes at Adelaide, which had a superior sensor and recorder) at the time of passage, at all stations except Cape Willoughby, on the eastern tip of Kangaroo Island. There the pressure response is strongly undular, and similar in many respects to the oscillations sometimes found behind the Queensland morning glory. The disturbance, which everywhere else is a cold front, but with some bore-like characters over the sea, arrives at Cape Willoughby with the *onset* of the undulations, as does the morning glory. The pressure trace may suggest that the gravity current, i.e. the cold front proper, arrived three hours later. However, we have no barograms to the east of Cape Willoughby, to find what happened when this complex structure reached the heated mainland, and two verbal wind change reports from the Coorong coast, between Adelaide and Mount Gambier, revealed nothing to distinguish the wind change there from that elsewhere. Indeed, they did reveal that the 'cool change' and windshift arrived there 'on time' and not three hours late. The pressure trace at Neptune Island has a wave-like feature behind the pressure jump (half-period ~ 12 min, peak to trough amplitude 0.4 mb) resembling some of the traces on Cape York Peninsula during the early stage of bore formation. In all cases the pressure jumps of 17 January 1969 are followed by a continuing rise in pressure as the synoptic trough moves away and the cold air apparently deepens.

The Adelaide 2300 temperature and humidity sounding was used to construct the Θ (virtual potential temperature) profile in Fig. 6. It is similar

Fig. 5 Weekly barograms from 5 of the stations named in Fig. 2, and a daily one from Adelaide, covering the change, whose arrival time is given to the right of each trace. The time and pressure scales are indicated.



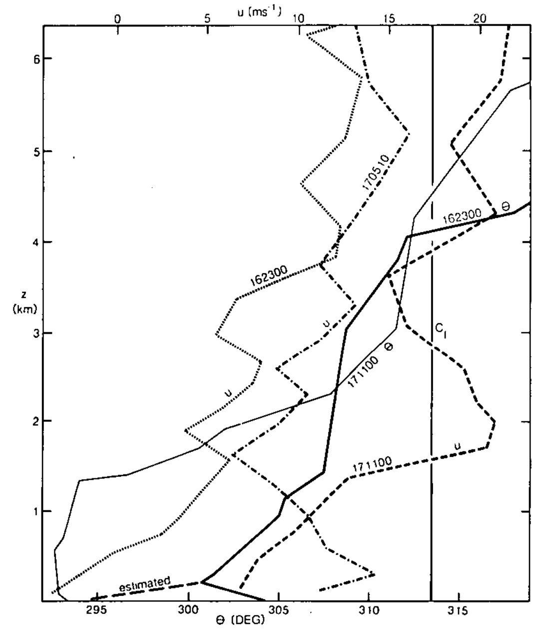


Fig. 6 Profiles of virtual potential temperature (Θ) and wind component normal to the front (u) at Adelaide before and after the frontal passage. Times of the soundings are indicated on the profiles, the first two digits referring to the date in January 1969, the next four to the times of commencement in hours and minutes. The vertical line c_f shows the speed of the front (17½ m s^{-1}).

in most respects to the profiles observed before the occurrence of morning glories on Cape York Peninsula: a fairly rapid increase with height in the lowest layers (up to about 1400 m in this case), capped by a nearly neutral layer extending to about 3000 m, in which the Brunt-Vaisala period was estimated as 21 min. The lowest part of the sounding has been adjusted by assuming a linear decrease of Θ from 210 m down to that of saturated air in contact with the sea (18-19 °C in January 1969 in the area south of the gulfs and north of Kangaroo Island) in place of the superadiabatic lapse measured at Adelaide. The exact structure over the sea is of course unknown, and is unlikely to have been linear. The 0200 h (near midday, local time) temperature measured at Adelaide (36 °C, dew-point 10 °C) indicates that during the three hours following the sounding an approximately dry adiabatic lapse must have been established up to at least 3000 m. Thus bore waves would have been impossible over land, but not over the sea a sufficient distance down-wind of the coast for the profile to resemble the adjusted one shown for Adelaide at 2300. This profile over the sea would be determined both by advection from the land and cooling by the sea.

Six hours after the arrival of the wind change at Adelaide, the sounding revealed that cooling had occurred up to 2300 m, the greatest being 16-17 °C up to about 1400 m. The change is clearly a cold frontal one there, brought about by horizontal advection strongly concentrated at the change line. The low level cooling could in no way have occurred through vertical motion, as in an internal bore.

Also shown in Fig. 6 are the profiles of u, the wind normal to the change line, before (by 6 hours) and after (by 10 minutes) the passage of the front. In the post-frontal wind sounding there is no level (at least below 6600 m) at which the normal wind component reaches the speed of propagation of the front; at 300 m above the surface the measured wind component maximum falls short of the propagation speed by 3 m s^{-1}, although the estimates based on the maximum wind gusts are in excess at this time.* The most marked change in the profile of u between 2300 on 16 January and 0510 on 17 January is the increase, centred in the lowest 300 m, and affecting only the lowest 1000 m. In the pre-frontal sounding the component u in the stratified boundary layer is small. Six hours after the frontal passage the normal component, and also the total wind, up to 1000 m had fallen, but that above 1600 m had increased, to exceed the propagation speed.

The cold front of 16 to 18 January 1969 over southern Australia

The roll cloud is but a minor episode in this major invasion of the southern part of the continent by cold air. At all places south of latitude 25 °S the event was unaccompanied by significant moist processes. There was never any doubt about the location of the front, marked as it was by a pressure jump and a sharp wind change, of a kind characteristic of summer. There was never observational evidence for other than a single front, except for the waves near Kangaroo Island, and a tendency for a double pressure jump (two jumps separated by as much as 30 to 90 minutes) late in the life of the front in eastern New South Wales. Figure 7 locates the front at 6-hourly intervals, and gives an indication of the changes in Θ at least partly due to the passage of the front, as determined by the routine soundings before and after frontal passage. The depth of cooling, H, is arbitrarily defined as that at which the cooling is half the maximum cooling, which is always at a low level. This convention was used to avoid the difficulty of deciding the often ill-defined top of the cooled layer. Also given are the average value of u up to the level H at the first sounding after frontal passage, and the speed of the front while moving

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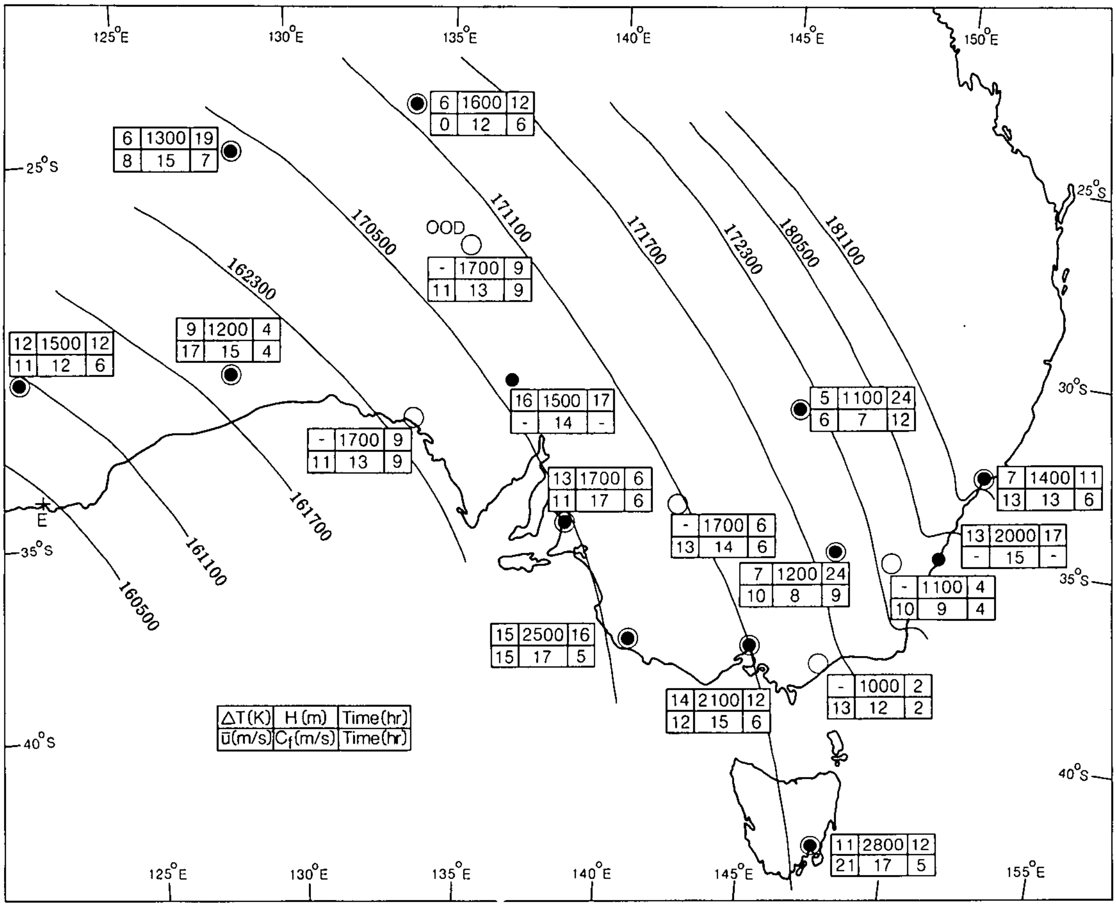
* The discrepancy between the measured u_{max} and that estimated from maximum gusts may be partly due to the fact that the wind sounding was done at the Airport, where the change was recorded as occurring 10 minutes earlier than at the Bureau in the city, where the anemogram was recorded.

Fig. 7 Isochrones of the cold frontal passage, with dates and times as in the profiles of Fig. 6. The aerological stations are shown by black dots (temperature sounding) and open circles (wind sounding). Near each is a grid showing (left to right) at top: maximum cooling (°C); height H (m) at which the cooling has decreased to only half that of the maximum; time of temperature sounding after frontal passage (hours); at bottom: average u to level H (m s^{-1}); speed of front (m s^{-1}); time of wind sounding after frontal passage (hours). E marks Esperance, OOD Oodnadatta.



over the station. 'Time after the front' is given in hours for both temperature and wind soundings. At stations without temperature soundings the depth H has been estimated from the wind soundings.

The advected cooling due to the front is substantial at all stations it was observed to pass, and is sustained through the lowest kilometre or two of the atmosphere. The broad result is that the front moves at about the mean value of the wind as found by the first sounding behind it, but there are some deficiencies. The picture for the two stations north of latitude 25 °S is complicated by the occurrence of moist processes and perhaps localised convection, but the large normal wind deficit is possibly significant. In the south, the most pronounced deficit in wind behind the front is at Adelaide, and, to a lesser extent, along the southern mainland coast. This indicates a non-stationary propagation of the front, with progressive flattening of the cold air, unless compensated by convergence parallel to the front.

Discussion

The bore of 17 January 1969

The change line over South Australian waters appears to have had a bore-like character, but over land it was a gravity current, sometimes evidently of an unsteady nature, with a closed circulation near its leading edge. It appears that the cold front can be transformed into a structure which is partly bore and partly gravity current, after encountering a stratified marine environment. It can then transform itself back to a gravity current when it reaches heated land.

To test the proposition that the event recorded in and to the south of Spencer Gulf on 17 January 1969 had bore-like characteristics, we have recourse to the simple bore theory analogy of Clarke (1983). According to this

$$c_b = F(c_o - u) + u \qquad \ldots 1$$

where c_o is the speed of small amplitude waves, u the normal velocity of the medium ahead of the bore, F a function of the normalised lifting at the bore, $\delta h/h$, and h is the depth of the undisturbed low-level stratified layer. F is defined by

$$F = \{1 + \tfrac{3}{2}\delta h/h + \tfrac{1}{2}(\delta h/h)^2\}^{\frac{1}{2}}$$

We also have seen that, in the absence of a strong curvature in the u-profile,

$$c_o = mG + u$$

where m = 0.90 for a straight Θ profile in the stratified air, and

$$G = \{ g/\Theta_u \int_0^h (\Theta_u - \Theta(z))\, dz \}^{\frac{1}{2}}$$

Here g is gravity, Θ_u the virtual potential temperature in the nearly neutral layer above the stratified layer and $\Theta(z)$ the virtual potential temperature in the stratified layer.

If a gravity current moving with supercritical speed c_f (c_f being greater than c_o in the invaded medium) Wood and Simpson's experiments show that the stratified layer is lifted bodily over the friction head of the invading current. One might expect that if a gravity current is propagating into an increasingly stratified environment, a stage would eventually be reached where the action of the current would be sufficient for c_b, as given by Eqn 1, to be equal to c_f. At this stage a bore, moving with the current and modifying its character, could be expected to form.

In the present case of the bore near Kangaroo Island, with the use of the Θ profile of Fig. 5, we obtain.

$$c_o \approx mG = 12.8 \text{ m s}^{-1}$$

and for a bore to move with the speed of the front

$$F \approx c_f/c_o \text{ with } c_f = 17\tfrac{1}{2} \text{ m s}^{-1}$$

The quadratic equation in $\delta h/h$ can then be solved, to yield

$$\delta h/h \approx 0.50$$

which with $h \approx 1400$ m gives $\delta h \approx 700$ m.

The magnitude of a pressure jump corresponding to the lifting of a stratified layer by δh can be estimated by

$$\delta p \approx \rho g \delta h \delta \Theta / \Theta_u \qquad \ldots 2$$

where $\delta\Theta$ is an average deficit in Θ in the lower layer (compared with the upper one of constant potential temperature Θ_u), given by

$$\delta\Theta = \Theta_u G^2 / (gh)$$

and ρ is air density. From this it follows that

$$\delta p \approx \rho G^2 \delta h/h = 1.1 \text{ mb}$$

which is about the magnitude of the observed pressure jump.

Thus, simple bore theory supports the conclusion that the gravity current propagating into the marine inversion near Kangaroo Island should result in a bore accompanying or slightly preceding the gravity current, with a pressure jump of about one millibar. Such a bore would become undular, and this is seen in one or two of the traces in Fig. 5.

There appears to be a close similarity between this event and those described by Lamb (1954) and Kirk (1961) at Malta, where they are evidently more common and more spectacular. The mechanism of formation is apparently provided in each case by a heated continent equatorward of a cool sea, and a cold front propagating into the cool marine stratified layer. Over the complex topography of the South Australian gulfs and Kangaroo Island there may well be a role in bore formation (by building up a sufficiently deep and intense marine inversion) for local circulations, such as land and sea-breezes and drainage winds, but this cannot be verified.

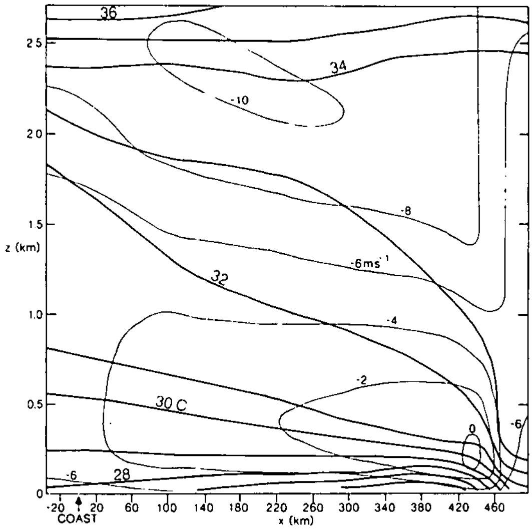
The cold front and offshore depression of 16-18 January 1969

The cold front at Adelaide, and evidently at other places, has the feature found by Clarke (1961, 1965, 1984), namely, a closed horizontal vortex near its leading edge, with descent occurring for a long way behind, flattening the layer of cold air, and perhaps leading to a 'breakaway' mass of cold air of decreasing depth. Such a sequence has been found in a numerical experiment conducted by Garratt and Physick (1986). These workers have succeeded in developing such features *ab initio* from a collapsing cold mass. Also, observing with a Doppler acoustic radar, they found a closed circulation (about 20 km wide) near the leading edge of the cold front associated with the disastrous bushfires on Ash Wednesday (16 February 1983) in Victoria.

The closed vortex has been found in sea-breeze circulations (Clarke 1984). An example of a sea-breeze front at 0145 (local time) with a closed vortex about 20 km wide near its leading edge, for conditions on Cape York Peninsula, is shown in Fig. 8. Both sea-breezes and cold fronts may evidently degenerate, according to the numerical experiments of Clarke (1984) and the two workers aforementioned, to a stage where the closed circulation vanishes, and the gravity current becomes a kind of wave.

The offshore depression accompanying the front

Fig. 8 A (two-dimensional) modelled sea-breeze front at 0145 local time at latitude 16.7°S on Cape York Peninsula in October, showing isopleths of potential temperature and (u-c), relative wind normal to the front, as functions of distance from the coast and height. Geostrophic wind is onshore at 5 m s^{-1}. Note that at this late stage in the history of the front, u-c is positive only in a strip 10-20 km wide just behind the leading edge. Everywhere else there is a deficit in the cold air flow behind the front, with consequent sinking motion and flattening of the cold air wedge. The sea-breeze surge or front is moving inland at 11.6 m s^{-1}, and the maximum vertical velocity associated with it is 0.14 m s^{-1} at 1400 m near its leading edge.



on 17 January 1969 bears a considerable likeness (because of the way in which it appears to hug the coast) to the depressions occurring around the coast of South Africa, as, for example, described and explained by Gill (1977). The non-linear sharpening of the trailing side of the trough, representing an increasingly well-marked gravity current, is much in evidence. The depression appears to have formed offshore in the western Great Australian Bight, and to have followed a course approximately along the coast, eastward and southeastward as far as Tasmania, before heading into the Southern Ocean. However, it can hardly be claimed as an example of coastal trapping, in view of the lack of significant orography around the southern Australian coast.

Conclusions

A midsummer Australian cold front may be intense, single, dry, extend to the centre of the continent, and marked throughout by pressure jumps of one or several millbars. Its character may vary, ranging from a circulation with a closed horizontal vortex near its leading edge, and extensive descent behind it (suggesting a continual flattening of the denser fluid layer) to a steadier structure at other places and times.

When such a complex encounters an environment stably stratified in its lower layers, as is sometimes found in southern Australian waters, the front may interact with the stable layer to produce a bore, which in time may become undular, and eventually decay to a train of solitary waves. The sequence of events following the encounter might be expected to depend (among other things) on whether the speed of the front is subcritical or supercritical with respect to the stably stratified layer into which it is propagating.

The subcritical case has been investigated by Crook and Miller, who showed that, in this case, a bore propagates ahead of the gravity current, as was found for the morning glory. In the supercritical case, which might be expected to occur more frequently in nature, the present study suggests a different course of events. The stable boundary layer, if it is lifted by an undercutting gravity current, may be raised sufficiently to enable a bore, formed at the leading edge, to propagate at the same speed as the current; that is, to so change the character of the phenomenon that it combines some of the properties of bore and gravity current, as has long been suspected from a study of surface autographic records.

The work of Wood and Simpson reinforces the conclusion, drawn from observations, that the same cold front can present either as a gravity current or as a bore, depending on the low-level stability of the pre-frontal environment.

The roll cloud and post-frontal pressure and wind oscillations are evidence of a bore-like character. In the absence of low-level stratification, no bore of this kind is possible, and the disturbance appears as a pure gravity current, as shown by the surface advective cooling at Adelaide on 17 January 1969.

Marked wind deficit (relative to the moving change line) behind the front is probably evidence of unsteadiness, indicating a sinking of isentropes for a long way to the rear of the sharp and dramatic leading edge, where strong upward motion is concentrated. It is perhaps significant that wind deficit was evident behind the front in *coastal* areas, which tend to form a boundary for many summertime fronts between an environment where bore-like behavior is possible and where it is not.

Bore-like cold frontal passages similar to the one reported here have been observed when a warm-season cold front invades the Mediterranean Sea following an incursion of warm air from north Africa.

Although it is probable that katabatic flow in sloping terrain can give rise to atmospheric bores (Clarke 1972), in all the cases of internal bores investigated here, the evidence points to some kind of gravity current as the activating mechanism, whether cold front, thunderstorm outflow, or, in the case of morning glories, sea-breezes. In all cases where investigation has been possible, it has been found that at least the early speed of the bore approximates to that of the gravity current, which recalls the process of bore formation by colliding sea-breezes on Cape York Peninsula.

Acknowledgments

Thanks are due to a number of the staff of the Bureau of Meteorology, both in Melbourne and in Regional Offices, for their courteous help with data. Especial gratitude is due to L. Marsh of the Adelaide office, and to A. G. Robin. The photographs by P. E. Geytenbeek and Flight Lieutenant E. J. Mannings provided a starting point for this work. Those provided by R. Hoebee showed that roll clouds can occur far inland in winter.

R. K. Smith and D. R. Christie are thanked for reading the manuscript.

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Appendix

The Daly Waters internal bore of 31 July 1974

During the Koorin Expedition (July to August 1974) pilot-balloon flights were performed at Daly Waters, Northern Territory, at hourly intervals, and radiosonde flights every three hours. Surface pressure was recorded at five stations within 100 km of Daly Waters every 20 minutes.

At 2300 on 31 July (0830 on 1 August local time) a long roll cloud with base about 300 m was observed moving overhead towards the northeast, where it was observed to dissipate within the next half hour. The 'lifted condensation level' of the surface air was 280 m at 2230. A pressure rise of 0.8 mb over 20 minutes was measured at the time of passage, but the strong semi-diurnal tide was responsible for some of this.

The temperature soundings (limited to 3 km in height) revealed a typical pre-bore structure at 2030, and a post-bore one at 2330, as shown in Fig. A1. The lifting δh produced by the bore can be readily deduced, on the assumption of conservation of potential temperature, to have been about 600 m for air parcels originally at 600 to 800 m, and the depth h of the stratified layer in the pre-bore medium is about 1000 m. The Froude number F is then

$$F = \{1 + \frac{3}{2}\,\delta h/h + \tfrac{1}{2}(\delta h/h)^2\}^{\frac{1}{2}} \approx 1.4$$

while

$$G = \{g/\Theta_u \int_0^h (\Theta_u - \Theta(z))dz\}^{\frac{1}{2}} \approx 7.8 \text{ m s}^{-1}$$

Neglecting the contributions due to the normal wind component and its curvature, we obtain

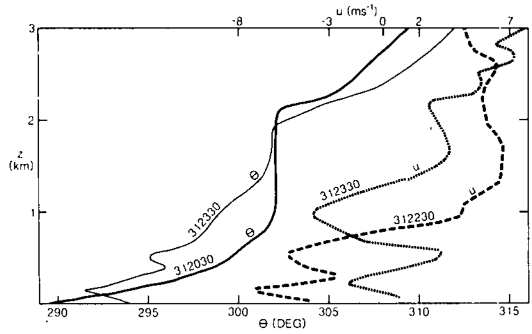
$$c_0 \approx 7.0 \text{ m s}^{-1}$$

and

$$c_b \approx Fc_0 \approx 10 \text{ m s}^{-1}$$

which cannot be checked, but is a likely value for

Fig. A1 Potential temperature and normal wind before and after the occurrence of an atmospheric bore at Daly Waters, Northern Territory, on 31 July 1974. This is the only 'before and after' set of soundings for a bore in the Australian area, apart from several on and near Cape York Peninsula. Note the stratified layer beneath a virtually neutral one, capped by an inversion representing the top of the fossil mixed layer from the previous day. The effect of the bore has been to lift the stratified layer by at least 600 m in its middle levels. The date and times of the soundings are entered on the graphs.



the bore speed. The pressure jump according to Eqn 2 should have been about 0.4 mb.

As can be seen from Fig. A1, the wind component u did change with the passage of the disturbance about 30 minutes earlier, but not conspicuously so, and there is no hint of a southwest component of 10 m s^{-1}, ruling out, as does the temperature sequence, the likelihood that the disturbance was a gravity current. The bore is thought to have originated at or near a cold frontal complex some 200 to 300 km to the southwest of Daly Waters, but no details are available.