The Southerly Burster of South Eastern Australia: An Orographically Forced Cold Front

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ABSTRACT

This paper presents an observational study of the "southerly burster", or "southerly buster", a particularly intense type of orographically and thermally influenced cold front which occurs in spring and summer along the southern coast of New South Wales in eastern Australia. It may have counterparts elsewhere. A brief review is given of the synoptic aspects of seventeen such fronts which occurred during the period January 1972 to January 1978. These had diverse origins, only rarely being fronts of Southern Ocean origin; mostly they developed ahead of Southern Ocean fronts. In all cases orographical effects appear to play an important role in genesis.

A more detailed study is made of two southerly bursters which occurred during an observational program held from 21 November 1982 until 13 December 1982, providing the synoptic background for a more detailed analysis of the structure of these phenomena in another paper. The first was particularly severe, producing wind gusts of up to 24.7 m s^{-1} and temperature changes of more than 21°C within an hour of its passage. Blocking of the front by the mountains of southeastern Australia was evident. A major feature of the second burster event was the multiplicity of prefrontal wind changes on the southern New South Wales coast and a roll vortex was observed in the postfrontal air. Most of the pressure changes in the postfrontal air of both fronts was attributable to the density difference between the pre- and postfrontal air masses and the rate at which the cold air deepened. Propagation speeds were also strongly affected by changes in the density difference. Twenty-four hour predictions using the ANMRC fine mesh numerical model showed favorable comparisons with mesoscale mean sea level pressure analyses, but the model was less successful in simulating the strong postfrontal pressure gradients and it underestimated the speed of fronts.

1. Introduction

The "southerly burster", or "southerly buster", is an intense cold front which occurs mostly in spring and summer months along the coast of New South Wales in eastern Australia, roughly between Gabo Island in the south and Port Macquarie in the north (Fig. 1). The name describes the arrival of the front which is usually marked by the sudden onset of strong southerly wind squalls of maritime origin which often replace hot northwesterlies originating over the continent. A burster is defined as "a squally wind change that produces strong southerly winds near the coast with gusts to at least 15 m s^{-1} soon after its passage, and which is not associated with a major depression over the Tasman Sea at New South Wales latitudes." Maximum gusts of 37 m s^{-1} have been recorded. The temperature changes can be dramatic also with falls of 10–15°C in a few minutes being common with strong bursters during the afternoon. Occasionally the leading edge of a southerly burster is marked by a spectacular roll cloud aligned perpendicular to the coast. However, precipitation is not usually associated with bursters. The abruptness of the wind change makes southerly bursters particularly hazardous to low flying aircraft and to persons involved in boating activities, especially when the front is unaccompanied by cloud.

As the front travels northward along the east coast it is deformed by the mountains of southeastern Australia and acceleration often occurs on the coastal side giving the front a characteristic S-shape on synoptic charts. Only rarely does the southerly burster originate directly from a Southern Ocean front; in most cases frontogenesis occurs ahead of a Southern Ocean front and can be rapid, with seemingly innocuous wind shift lines sometimes developing into a major disturbance in a period of twelve hours or less.

Over the ten year period 1974–83, 95 southerly bursters occurred at Sydney Airport confined to the months September to March inclusive. Sixty-two percent of

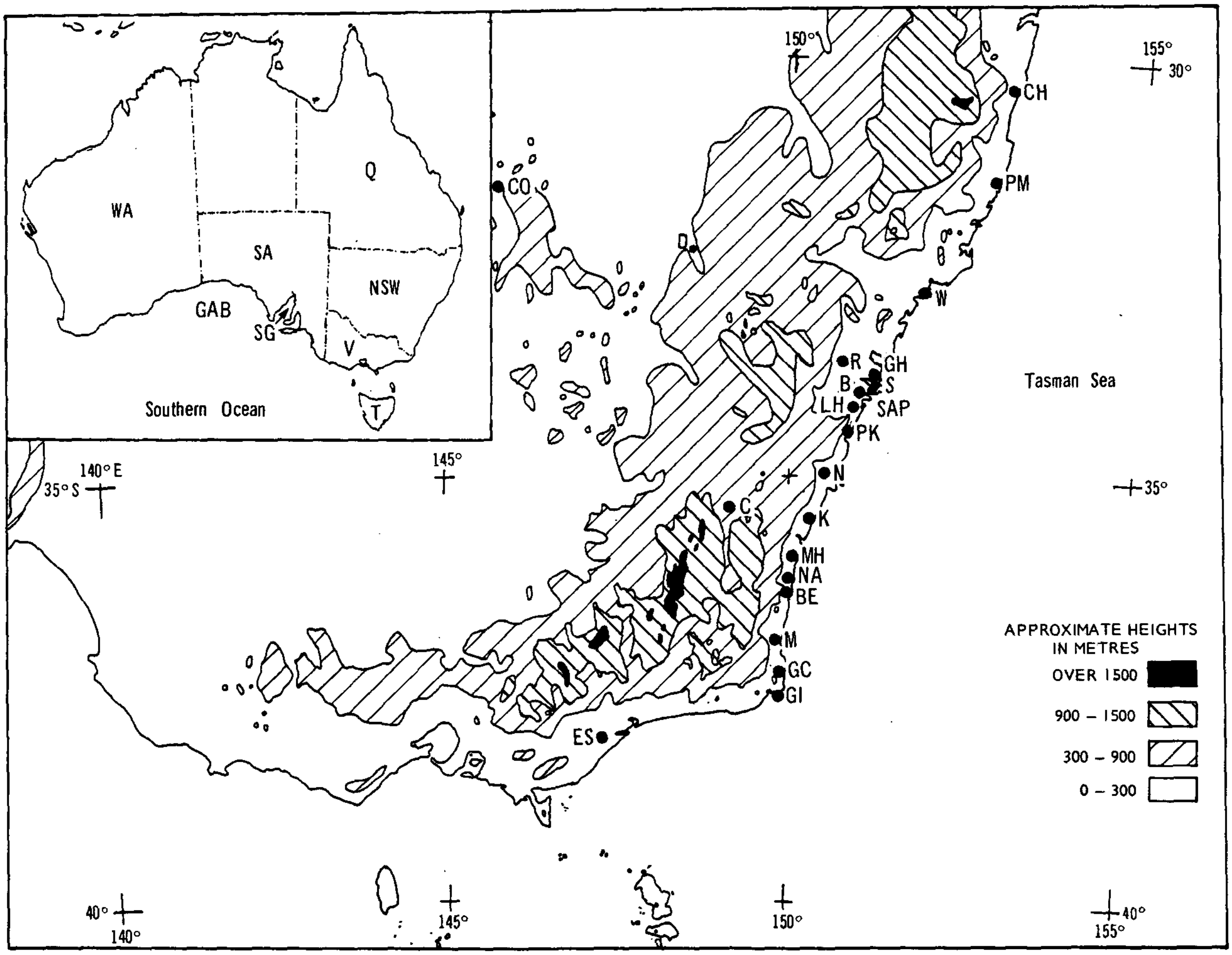


FIG. 1. Map of southeastern Australia showing locations cited in text, topographical contours (m) and (inset) the States. Abbreviations are as follows: B—Bankstown; BE—Bermagui; C—Canberra; CH—Coffs Harbour; CO—Cobar; D—Dubbo; ES—East Sale; GAB—Great Australian Bight; GC—Green Cape; GH—Gore Hill; GI—Gabo Island; K—Kioloa; LH—Lucas Heights; M—Merimbula; MH—Moruya Heads; N—Nowra; NA—Narooma; NSW—New South Wales; PK—Port Kembla; PM—Port Macquarie; Q—Queensland; R—Richmond; S—Sydney; SA—South Australia; SAP—Sydney Airport; SG—Spencer Gulf; T—Tasmania; V—Victoria; W—Williamtown; WA—Western Australia.

the events occurred between the hours of 1300 and 2100 local time; all the events with wind gusts of 23.2 m s^{-1} (45 kt) or more occurred between 1000 and midnight local time. Bursters were most frequent in December (2.3 per year) and November (1.7 per year) and least frequent in September and March (0.7 per year). Twenty-nine percent of bursters were strong (gusts of 20.6 m s^{-1} (40 kt) or more) and one percent had gusts of 25.7 m s^{-1} (50 kt) or more. These statistics should be a good indication of the frequency and strength of bursters at locations near the coast from about Kioloa to Newcastle.

While the southerly burster is a local phenomenon restricted to the coastal region of New South Wales, there is evidence that fronts with similar characteristics occur in other parts of the world. It is likely that the "Pampero Sucio" of South America, a sometimes violent squall line of summertime which moves northwards along the eastern side of the Andes (Meteorological Reports, 1948), is a closely related phenomenon. Shallow fronts encountering the South Island of New Zealand are similarly constrained to move along the mountain chain from the southwest (Hutchings, 1944). In the Northern Hemisphere, the "backdoor fronts" of the eastern United States appear to have features in common with the southerly burster. Heat waves which occur in the mid-Atlantic States in spring and summer are often broken by fronts moving from a northerly or easterly direction as cold air is banked up and forced southwards along the eastern side of the Appalachian mountains (Carr, 1951, Bosart *et al.* 1973). A recent study of an intense southward moving cold front on the eastern side of the Rocky Mountains by Lilly (1981) shows that this also had characteristics similar to the southerly burster. Finally the low pressure systems which move around the coast of southern Africa in an anticlockwise sense from west to east appear to be coastally trapped disturbances (Gill, 1977) and as such may have dynamical features in common with some southerly bursters.

An early description of the southerly burster is given in an essay by Hunt (1894), regional aspects are discussed by Gentilli (1969) and a more comprehensive study is presented by Colquhoun (1981). The mesoscale structure of such disturbances has been captured in simulations using a Moveable Fine Mesh (MFM) numerical model (Gauntlett *et al.* 1984) and Baines (1980) describes an analytical model in which the phenomenon is modeled in a dry incompressible two layer fluid system. Christie and Muirhead (1983) used sensitive recording micro-barometers to investigate southerly bursters and concluded that some may be attributable to the presence of solitary waves in a stable maritime inversion waveguide.

For the three week period from 21 November to 13 December 1982 a Southerly Burster Observational Program (SUBOP) was conducted, the objectives being to test the analytical model of Baines, to further test the MFM model of Gauntlett *et al.*, and to provide more detailed information on the structure of the southerly burster, especially over the sea. In addition to the normal synoptic network, data were obtained from a special anemometer network, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) aircraft and serial pilot balloon and radiosonde flights. Over this period there were seven occasions when persistent southerly winds developed or southerly changes occurred on the New South Wales coast. Some changes were due to the movement of lower tropospheric troughs from the land to the sea. Two burster events occurred on 25 November and 1 December. The other changes on 23 and 27 November, 3, 6 and 7 December were weak.

This paper discusses the synoptic aspects of bursters, provides background information on the synoptic scale of the SUBOP bursters for the further analysis of the structure of these phenomena in another paper (Coulman *et al.*, 1985), and explains the weather forecasting implications.

2. A study of seventeen strong southerly bursters

A brief summary of a study of strong southerly bursters over the period January 1972 to January 1978 by the first author (Colquhoun, 1981) is appropriate. Seventeen strong southerly bursters occurred during this period. A strong burster is defined as one producing wind gusts of 21 m s^{-1} or more. Dines anemometer records from Port Kembla and Sydney Airport were used to select the events. These data, with anemograph records from Williamtown, temperature data from an instrumented tower at Gore Hill, Sydney, and the MSL isobaric and upper level charts were used in an attempt to deduce the origin, evolution and structure of the bursters. In all of these events the arrival of the burster was defined as being when the wind direction changed to the south.

a. Origins and evolution of bursters

The bursters had diverse origins and were only rarely (two occurrences) fronts of Southern Ocean origin. Mostly they developed ahead of Southern Ocean fronts, four of them over Western Australia, five near the coast of eastern Victoria and six near the New South Wales coast. Local frontogenetic events of this nature increase the difficulties of forecasting the occurrence of significant weather changes. Distortion of the fronts by the mountains of southeast Australia was evident in each case with penetration to the New South Wales central coast occurring on many occasions before the front reached Canberra. Cassidy (1945) also observed this evolution. The maximum northward extent of the wind changes from MSL analyses showed that most reached 27°S, and one penetrated as far as 24°S.

Five of the six occurrences of frontogenesis near the New South Wales coast were associated with mesolow development. All of the lows were very shallow, no circulation being evident at the 850 mb level. Figure 2 shows one such development on 2 December 1972. At 1500 Eastern Daylight Saving Time (EDST) mesoscale low pressure centers were over northeast Victoria and just west of Moruya Heads (Fig. 2a). A cold front was lying from eastern Victoria along the Victorian mountains to northern Victoria and then to western New South Wales and a sea breeze front (shown by a dashed line) lay just inland from the New South Wales coast. There was a 10°C temperature difference between Moruya Heads at the coast and a town further to the south but 13 km inland. By 1800 EDST (Fig. 2b) the front had just passed Gabo Island and the low near the coast had moved to the northeast and was probably centered just off the coast. Winds on the New South Wales south coast, previously north or northeasterly, had veered to the southeast. By 2100 EDST (Fig. 2c) the coastal low had produced wave development on the seabreeze front; south of the wave the seabreeze front had developed cold frontal characteristics and was moving toward the northwest. This burster produced wind gusts of 26.8 m s^{-1} at Port Kembla and 26.3 m s^{-1} at Sydney Airport. One mesolow event on 22 December 1972 was of very short duration. The strong winds lasted for one hour and the wind was calm two and a half hours after the wind change.

b. Upper tropospheric conditions

A brief study of upper tropospheric conditions associated with these seventeen cases indicated than when bursters are near the New South Wales central coast:

(i) they may be associated with either large amplitude or weak 500 mb troughs, or even with pronounced

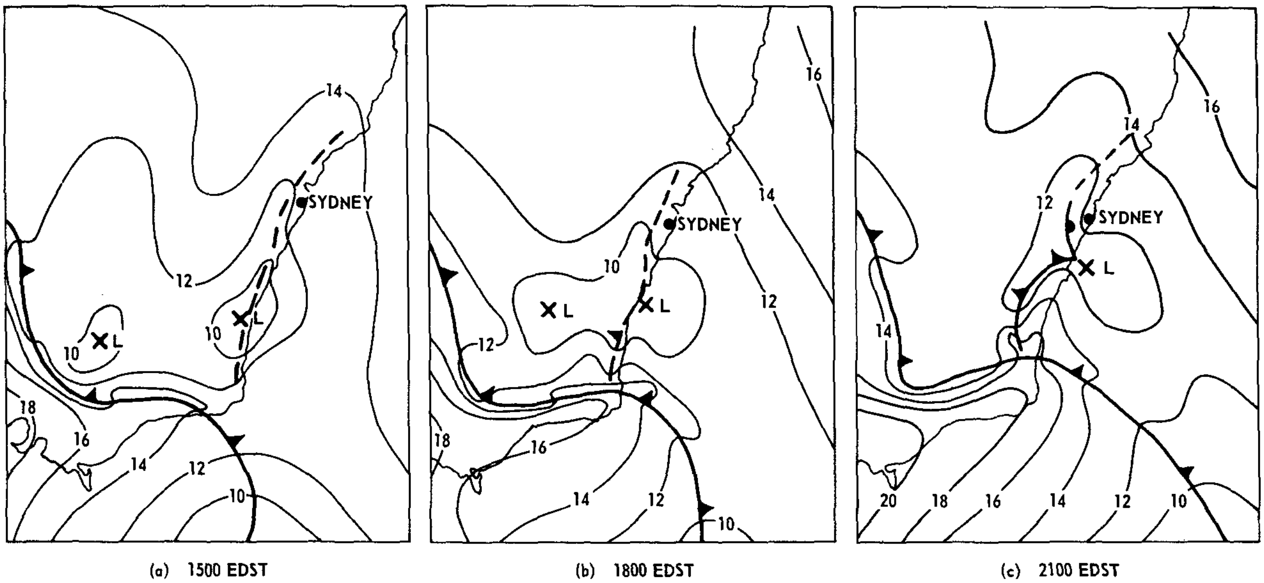


FIG. 2. Mean sea level isobaric (mb, first two digits omitted) charts at (a) 1500 EDST, (b) 1800 EDST and (c) 2100 EDST 2 December 1972 showing a southerly burster associated with mesolow development.

ridges (29 percent were ridge situations and the remainder trough situations);

(ii) the 300 mb jet axis was usually well to the south of the position of the leading front;

(iii) the 500 mb flow was diffluent and from a direction south of west in three of the five cases when mesoscale lows developed over the land and then produced frontogenesis as they moved to the sea. The 300 mb flow was diffluent in one of the remaining cases.

c. *Mesoscale structure and wind and temperature variations*

Clarke (1961) determined the mesoscale structure of dry cold fronts using serial pilot balloon flights, radiosonde, and aircraft data and found closed circulations (roll vortices) in the velocity fields behind several fronts; in two cases, double circulations with the roll vortices having durations of from 15 minutes to an hour were inferred. Comparison of his Fig. 11c and Fig. 15 shows that sharp increases in surface wind speed accompanied the arrival of roll vortices and suggest that the presence of roll vortices can be tentatively inferred from surface anemographs. Attempts were made to infer the structure of the seventeen bursters from anemograph data and temperature profile measurements. The arrival of a clockwise rotating vortex (where the vortex is being viewed from the west) being associated with an increase in wind speed and instability and a decrease in temperature; and the highest wind speed occurring under the circulation center of the vortex. Roll vortices were thought to be associated with fifty-three percent of bursters. Figure 3 shows as an example the structure deduced for the southerly burster of 11 December 1972 and the Dines anemograph trace at Sydney Airport on which it is based. The first circulation cell corresponds with the 28 minute period following the first wind change and the second cell with the subsequent two hour period. Several of the changes on other days showed more complex wind speed variations making interpretations of frontal structure rather difficult, and in some cases the structures shown in Colquhoun (1981) are rather speculative.

Figure 4 shows the wind speed fluctuations at Port Kembla, Sydney Airport and Williamtown for the burster of 20 November 1973 and gives some idea of the evolution in structure with movement northwards. The anemograph traces are arranged so that the maximum gusts are vertically coincident. While there are some similarities in the three traces, for example the maximum gust occurs just after the change, there are obvious differences. In particular, there was no period of calm at Port Kembla compared with the other stations and the period of calm at Sydney was shorter than that at Williamtown further to the north. We return to this observation later.

In general, temperature changes associated with burster events at Gore Hill were greatest with afternoon changes and the temperature always fell after the wind changes occurring during this period. Temperature changes associated with evening bursters were sometimes complex. On 2 December 1972 a slight decrease in temperature followed the wind change, however about five minutes later the temperature rose 3°C in two minutes then fell 6°C in the next 16 minutes. The immediate postfrontal lapse rates of most afternoon changes showed extreme instability due to the transfer of heat from the hot land surface to the maritime air being advected inland. With those occurring at night

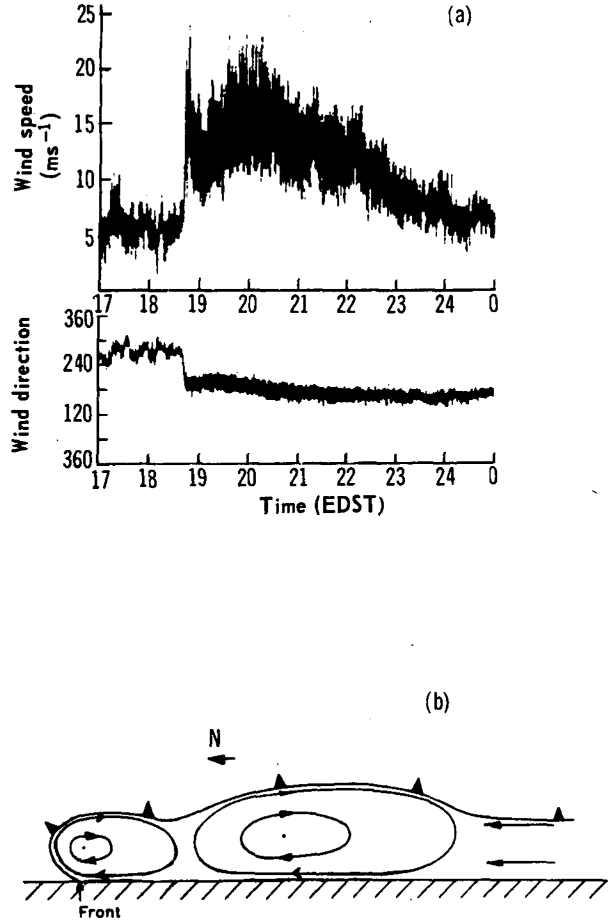


FIG. 3. (a) Variations in wind speed (m s^{-1}) and direction at Sydney Airport between 1700 EDST 11 December 1972 and 0100 EDST 12 December 1982, and (b) schematic representation deduced from these wind data and other temperature data, of the frontal structure in a vertical cross section parallel to the coast. Streamlines represent airflow relative to the circulation centers of the roll vortices and straight arrows indicate wind directions.

the postfrontal lapse rate was not as great but conditions were unstable.

Figure 5 shows the base level thermograph (10 m AGL) and the lapse rate between the 10 and 110 m levels at Gore Hill, also for the event of 20 November 1973. Noteworthy features of the lapse rate variations are the increases in stability just before the change in the base level temperature, the extreme instability (lapse rate 6°C/100 m) just after the change followed by the period of inversion conditions. While it is difficult to relate some of the lapse rate variations at Gore Hill to the wind speed changes at Sydney Airport (Fig. 4), three major changes or features appear to be connected: the first Sydney Airport change at 1710 EDST and the extreme instability beginning at 1727 EDST at Gore Hill; the light winds and inversion conditions; and possibly the increase in wind speed about 1842 EDST and the instability at 1855 EDST.

3. Two southerly burster events

a. The burster of 25 November 1982

This event was notable in that it was preceded and accompanied by dust storms and record November maximum temperatures (41.8°C at Sydney) occurred in the prefrontal air. There was no precipitation associated with the event. It illustrates the analysis and forecasting difficulties which occur over southern Australia when frontogenesis occurs ahead of a Southern Ocean front.

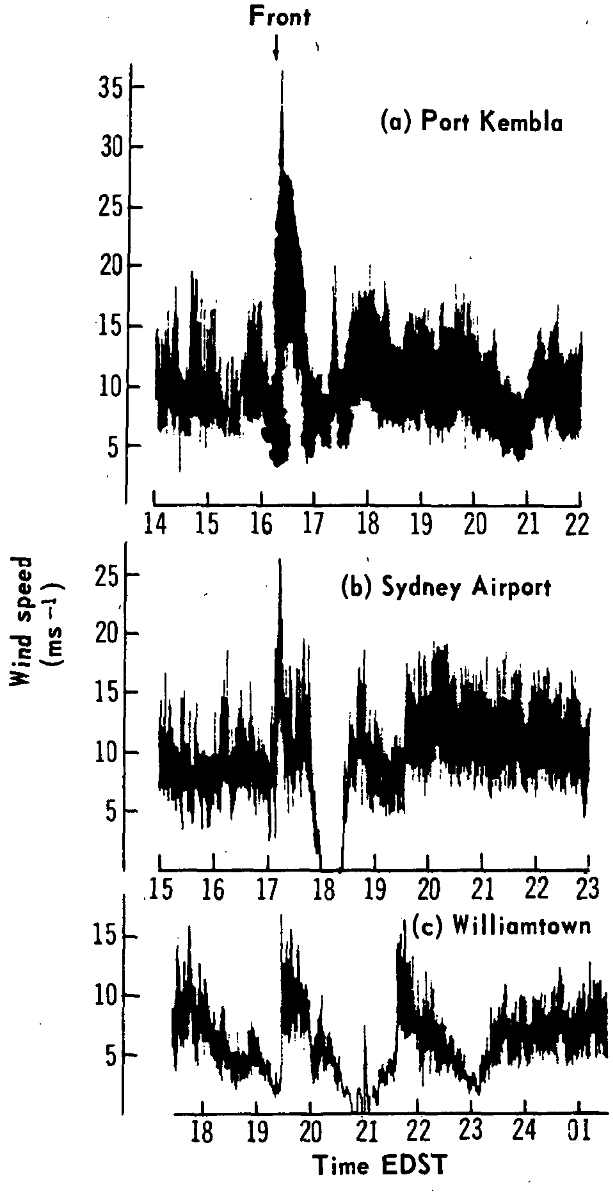


FIG. 4. Copies of anemographs at (a) Port Kembla, (b) Sydney Airport and (c) Williamtown showing variations in wind speed (m s^{-1}) on 20 November 1973. Relative to Fig. 3a the time scales of Figs. 3b and 3c are displaced so that the maximum gusts are vertically coincident.

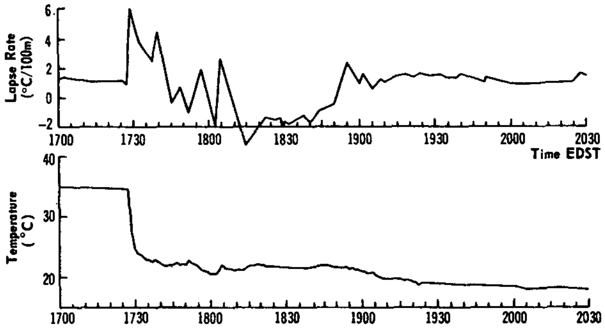


FIG. 5. Variations in base level (10 m above ground level) temperature (°C) and lapse rate (°C/100m) between the 10 and 110 m levels on 20 November 1973 at Gore Hill between 1700 EDST and 2030 EDST.

The front had its origins in a western australian trough which by 0600 EDST 24 November 1982 (Fig. 6) extended from the center of Western Australia toward the Victorian coast; a Southern Ocean front was approaching the Great Australian Bight. A ridge existed at 500 mb over the surface trough and at 300 mb there was a jet well south of the continent. Frontogenesis occurred as the thermal contrast across the surface trough increased substantially during the morning. This is verified by a more than 20°C temperature difference between surface temperatures over South Australia and a ship 300 km southwest of the coast. The front then moved northeastward and was lying along the South Australian coast at 1500 EDST. Two prefrontal troughs, or wind shift lines, were evident over the land at this time. Doswell (1982) says that these lines are common in the United States but that their cause is not known. The transitory nature of the wind shift lines is shown by the synoptic situation at 0300 EDST 25 November 1982 (Fig. 7) where only one is analyzed ahead of the new front.

The further evolution of the wind shift line/front system illustrates the difficulties identifying and timing the arrival of fronts. Two discontinuities were evident at the southernmost coastal anemometers (Green Cape and Merimbula), the first probably being the prefrontal trough and the second the front; however, further to the north only one was observed. Frontogenesis is thought to have occurred on the coastal section of the prefrontal trough.

Isochrones of frontal positions between 0600 EDST 25 November 1982 and 0100 EDST 26 November 1982 are shown in Fig. 8 together with the times at which the front was located by the CSIRO aircraft. The retardation of the front by the mountains of southeastern Australia was pronounced with frontal passage occurring at Coffs Harbour (see Fig. 1) and Canberra at almost the same time. The average frontal speed between Moruya Heads and Coffs Harbour was 12.7 m s^{-1}; between Moruya Heads and Canberra it only was 2.1 m s^{-1}. The coastal speed at 0900 EDST, 9.0 m s^{-1}, had almost doubled to a maximum of about 17.0 m s^{-1} at 1500 EDST. This speed change corresponded with an increase in the temperature gradient across the front, as detailed in Table 1. Coulman *et al.* (1985) compare these observed speeds with those obtained from density current theory using both aircraft and radiosonde temperature data. The decrease in temperature of the postfrontal air was due to a change in its trajectory. At 0900 EDST its recent history was overland. Coulman *et al.* show that, close to the coast,

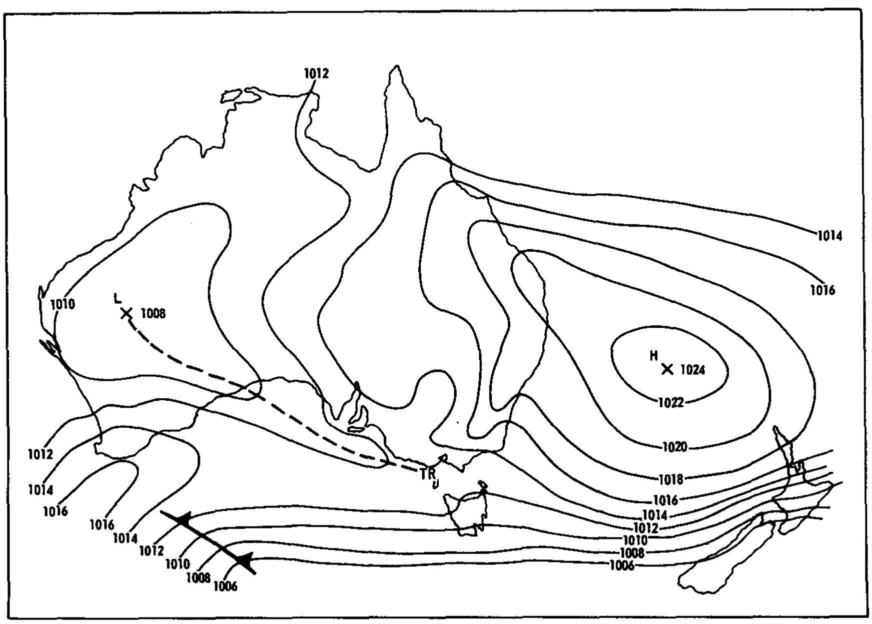


FIG. 6. Mean sea level isobaric (mb) chart 0600 EDST 24 November 1982.

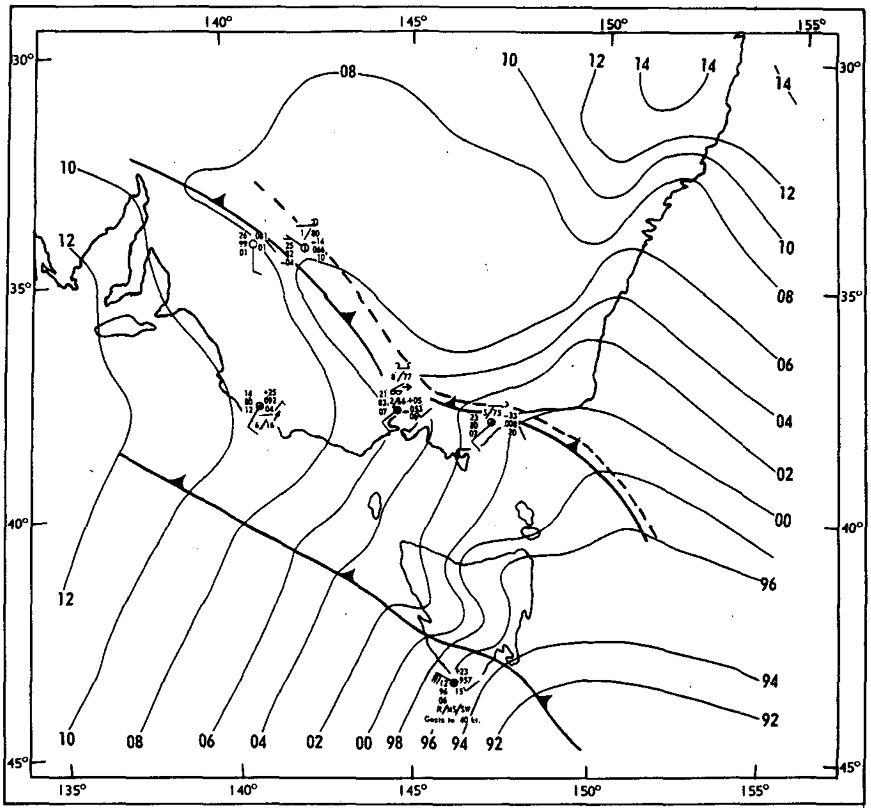


FIG. 7. Mean sea level isobaric (mb, first two digits omitted) chart 0300 EDST 25 November 1982. Plotting of observations on this and subsequent diagrams is in accordance with Southern Hemisphere convention.

this air mass had not adjusted to the sea surface temperature but further seaward the air mass had adjusted. However, as the front advanced further northward the trajectory of the postfrontal air mass was completely over the sea and hence cooler. The modification of the boundary layer air due to an overland trajectory was still evident at 1500 EDST. The temperature at Gabo Island in the maritime air mass was 16°C, modified air at Merimbula was 22°C and further north at Moruya Heads the air was of maritime origin and 19°C.

Figure 9 shows the MSL pressure charts at (a) 0900 EDST (b) 1200 EDST and (c) 1500 EDST with additional inputs of surface pressures and Doppler winds (m s^{-1}) derived by the aircraft. The only pressure values used are those at aircraft heights of 100 m or less. Winds in Figs. 9b and 9c are plotted so that they are at the position, relative to the front, they would have been at the observation time. In Fig. 9a a mesoscale low pressure center is shown northeast of Green Cape. This appears to be near the boundary of the maritime air and the air with a recent land trajectory and may have been topographically induced. The increase in the postfrontal pressure gradient during the day is evident and is consistent with the increasing temperature gradient across the front. The gradient measured along the coast immediately south from the front was 2.0 mb/50 km at 0900 EDST, 2.5 mb/50 km at 1200 EDST and 4.3 mb/50 km at 1500 EDST. Aircraft derived winds over the sea at 0909 and 1450 EDST also reflect this strengthening gradient.

At 1500 EDST 25 November evidence of blocking of the low level flow by the Victorian mountains is to be found in the 850 mb streamlines and isotachs of Fig. 10, in the observation of a wind of 20.5 m s^{-1} from 260 deg at East Sale at 1500 EDST and 25.5 m s^{-1} from 270 deg six hours previously. Upwind of the mountains winds were only about half these speeds. Figure 10 also shows the shallowness of the burster as winds at 850 mb were westerly over the New South Wales coast. At 500 mb a weak trough was in the same position as at 850 mb and at 300 mb the jet stream was over northern Tasmania.

By 0900 EDST 26 November 1982 the front had moved to the Southern Queensland coast (see Fig. 11), but was quasi-stationary along the New South Wales mountains.

Some observations from selected stations indicate the severity of the changes associated with this phenomenon. The temperature fell 18°C at Sydney within an hour of the occurrence of the burster and extremely unstable conditions between the heights 10 and 110 m above ground level were evident immediately following

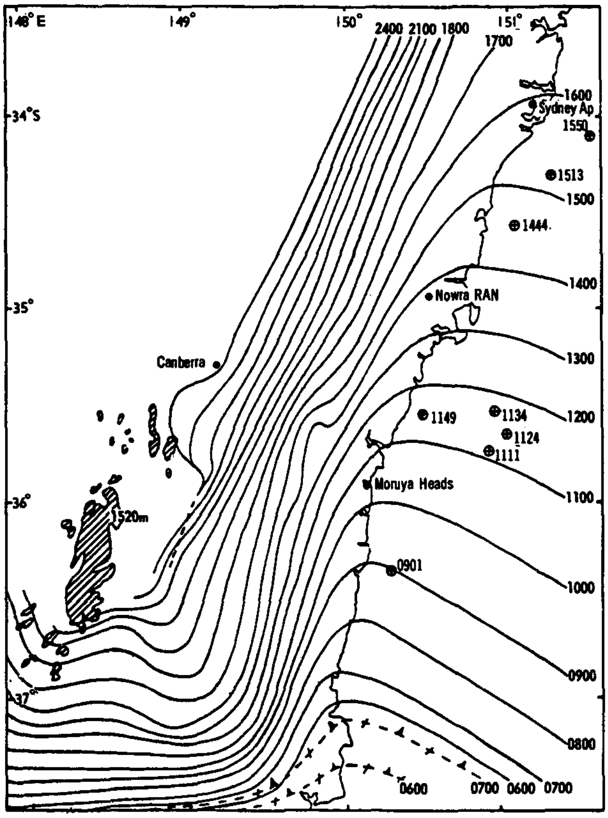


FIG. 8. Isochrones of frontal position between 0600 EDST 25 November 1982 and 0100 EDST 26 November 1982. Front locations over the ocean, determined by the CSIRO aircraft, are shown with a circled cross and the times (EDST) of location are indicated.

the front, with an initial lapse rate of 7.4°C/100 m (Fig. 12). The increasing stability over the hour prior to the front was probably caused by the decrease in surface temperature which was associated with an increase in middle level cloud. There is little difference in the temperature changes at Nowra, Sydney Airport and Richmond (Table 2), but the change becomes smaller as the front moves north of Sydney and at Coffs Harbour the temperature actually rose following the change. This last result is not paradoxical and was found in some instances by Clarke (1961) who attributed it to mechanical stirring of the surface inversion. Garrett *et al.* (1985) also discuss this phenomenon.

The strongest wind gust recorded by a permanent anemograph at standard exposure was 24.7 m s^{-1} at Sydney Airport. Over the six years of the investigation described in Section 2, seven of the seventeen strong burster events registered gusts of at least 24.7 m s^{-1} at Sydney Airport, and the highest gust was 27.3 m s^{-1}. Although the immediate postfrontal winds near the coast were southerly, further inland they were southeasterly and, on parts of the tablelands had backed further to be from the eastnortheast.

The data from the radiosondes released in the postfrontal air from Nowra at 1350 and 1500 EDST and in the prefrontal air from Sydney Airport at 1500 EDST are shown in Fig. 13. Also shown are the pre- and postfrontal soundings made by the aircraft. Over the land, the prefrontal air is very hot and dry due to its recent continental trajectory, and the lapse rate is superadiabatic to about 740 mb, or 2.69 km. As this air was advected over the cooler ocean surface, a strongly stable, but shallow, boundary layer developed. The postfrontal soundings show a well-mixed layer, due presumably to mechanical and convective turbulence. At Nowra, there is an appreciable superadiabatic lapse rate in the near surface layer, again evidence of strong instability as the residual heat in the previously hot land surface is released. Accordingly, the mixed layer over the sea is not as deep as at Nowra at 1500 EDST. Although the Nowra soundings indicate an increase in the depth of the postfrontal air; there is little change over the period between the two soundings in the thickness of the frontal inversion layer.

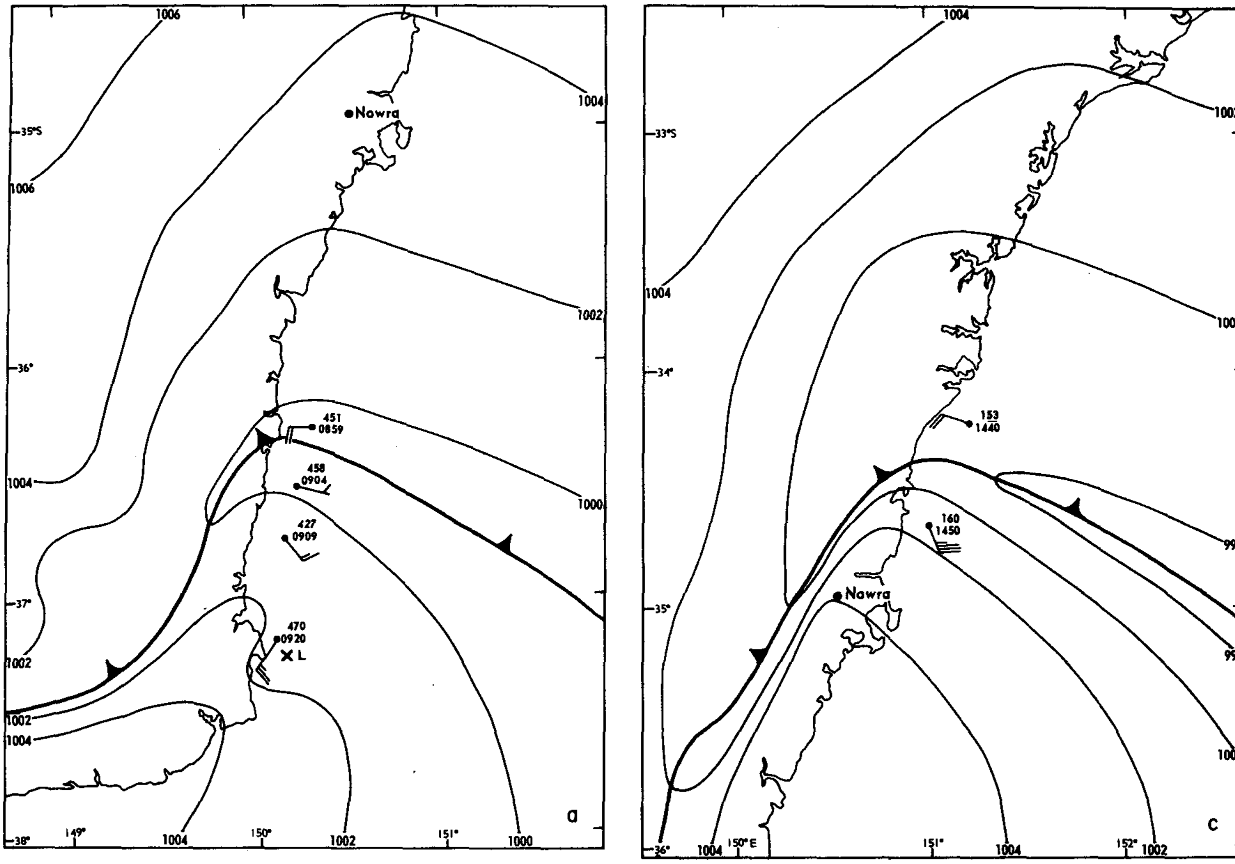
b. The burster of 1 December 1982

Analysis of this event was more difficult than the previous one. Added complications which illustrate the forecasting difficulties are mesolow development on wind shift lines over Victoria, multiple wind shift lines on the New South Wales coast, and mesohigh development due to the outflow from thunderstorms. This burster had its origins in a trough that lay over Western Australia on 27 November 1982. The trough extended southeastward toward Spencer Gulf during 28 November and the following day frontogenesis occurred and a prefrontal windshift line developed. During 30 November the system moved across western Victoria, several mesolows developed on the windshift line and at 1800 EDST there are some data suggesting the formation of a second windshift line (see Fig. 14). This complex system moved eastward ahead of a Southern Ocean cold front which has passed over the Great Australian Bight during the day. By 0300 EDST 1 December 1982 the prefrontal troughs extended from the northwest of New South Wales to the eastern Victorian coast (Fig. 15).

Despite multiple changes evident on the analyses only one discontinuity was indicated by the Green Cape anemograph record, and this occurred just before 0900 EDST with the passage of the surviving windshift line,

TABLE 1. Temperature difference ΔT, measured over a distance of about a degree of latitude across the front, and temperature of the immediate postfrontal air T_c, on 26 November 1982.

Time (EDST)	ΔT (°C)	T_c (°C)
0900	7	26–27
1200	14	22
1500	22	21



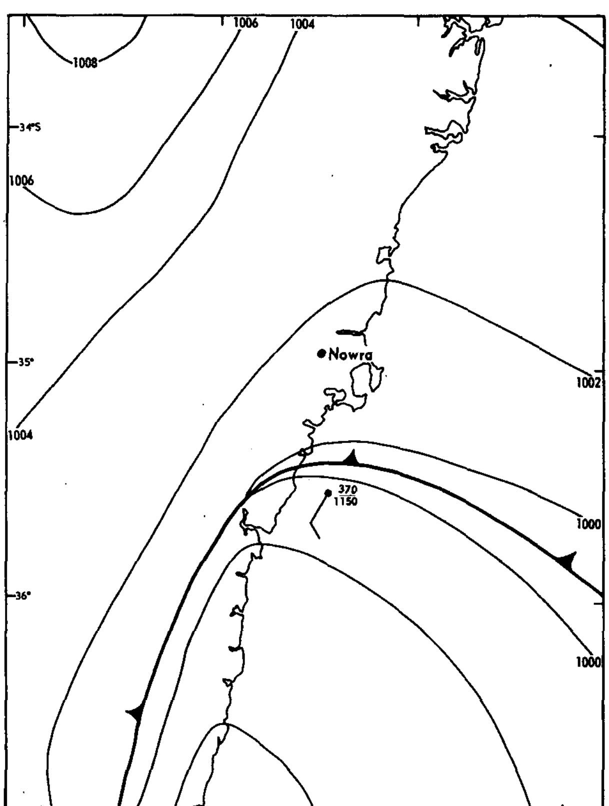


FIG. 9. Mean sea level isobaric (mb) charts at (a) 0900 EDST, (b) 1200 EDST, and (c) 1500 EDST on 25 November 1982. Data plotted over the ocean, derived from CSIRO aircraft data, are winds (m s^{-1}, full pennant 5 m s^{-1}, half pennant 2.5 m s^{-1}), height of aircraft (m) and time of observation (EDST). Aircraft data in (b) and (c) are plotted so that they are at the position, relative to the front, they would have been at the chart time.

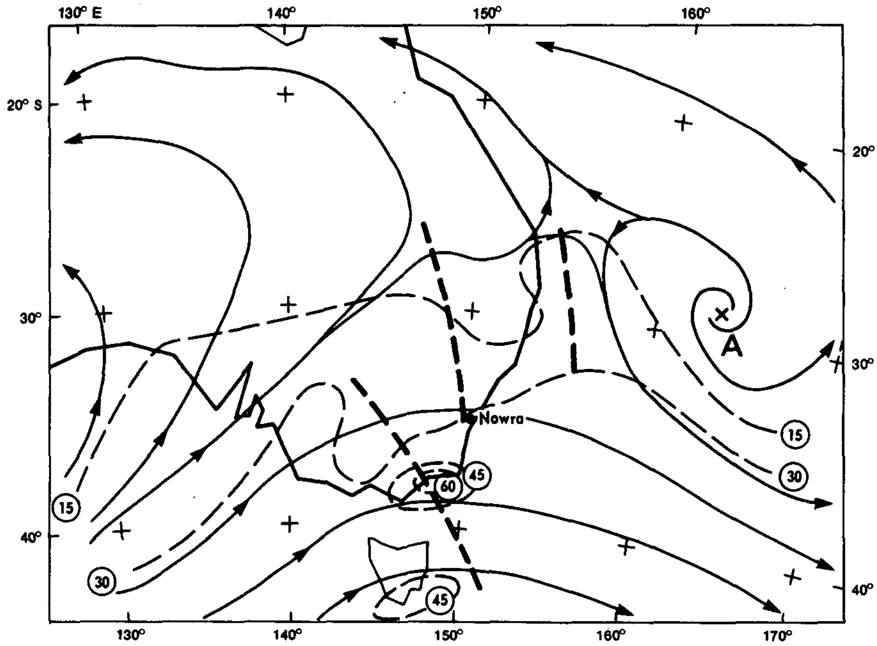


FIG. 10. Streamline (full lines) and isotach (dashed lines, kt) analysis at 850 mb, 1500 EDST 25 November 1982. Trough lines are shown by thick dashed lines.

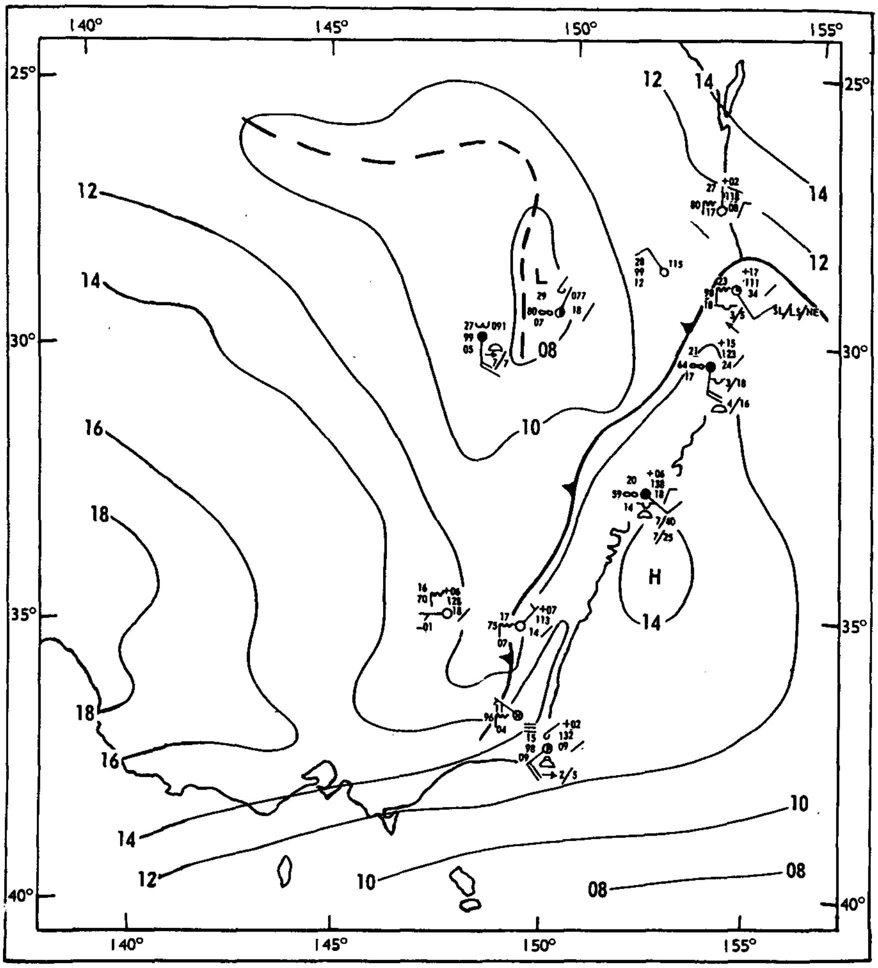


FIG. 11. Mean sea level isobaric (mb, first two digits omitted) chart 0900 EDST 26 November 1982.

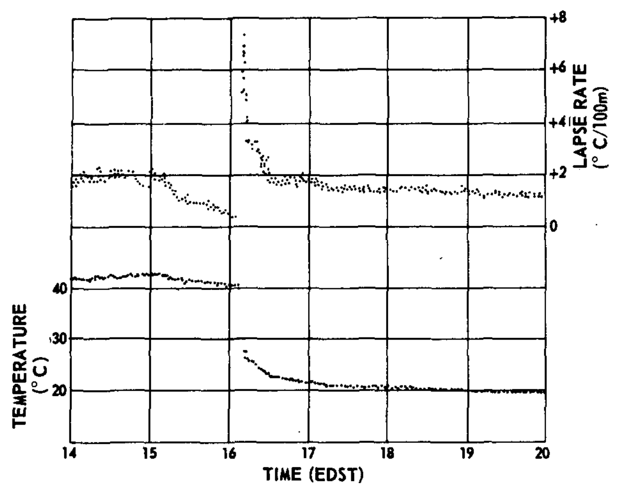


FIG. 12. Variations in 10 m level temperature (°C) and lapse rate (°C/100 m) between the 10 and 110 m levels at Gore Hill, Sydney, between 1400 and 2000 EDST on 25 November 1982.

which by this time was developing frontal characteristics.

Interpretation of the anemograph data from the New South Wales Coast is difficult. Even though only one discontinuity occurred at Green Cape, two were detected at Merimbula, Bermagui, Narooma and Kioloa, while three were evident at Moruya Heads. The first discontinuity at Moruya Heads involved a change in wind direction but the second and third were mainly speed changes. Synoptic data indicate that there was a lower tropospheric temperature inversion over the South Coast during the morning. The discontinuities developed as the front moved into this inversion layer. Figure 16 shows the locations of the initial discontinuity (full lines) at hourly intervals. Also shown (dashed line) is the position at 0900 EDST of the windshift line which caused the one discontinuity at Green Cape. Discontinuities at 1000 and 1100 EDST are new developments. CSIRO aircraft observations show that they were less than 450 m deep at 1136 EDST. The discontinuity located by the aircraft at 1136 EDST may have been the developing front which passed Green Cape just before 0900 EDST.

The complexity of the synoptic situation is shown by the MSL pressure analysis at 1500 EDST 1 December (Fig. 17). Thunderstorm activity over northeastern New South Wales and southeastern Queensland had produced a mesohigh/mesolow coupled with an 11 mb pressure difference between the centers. As in the previous event, movement across the tablelands of New South Wales was slow; however, this front penetrated further to the west, crossing most of the tablelands area in the south of the state by 0300 EDST 2 December. The 500 mb analysis at 1500 EDST 1 December showed a trough lying from the southeastern to the northwestern corners of New South Wales and at 300 mb a jet stream was between Victoria and Tasmania.

Generally gust strengths were less than those of the previous event, as were the temperature contrasts between pre- and postfrontal air masses (Table 3). The temperature at Gore Hill fell 11°C within an hour of the arrival of the burster. The lapse rate decreased for the three hours up to ten minutes prior to the burster then increased, becoming unstable soon after the passage of the front. Unlike the event on 25 November the increasing stability was not associated with a decrease in surface temperature, but may have been a result of prefrontal subsidence.

The low level wind field near Nowra was determined for this event by tracking 30 gm helium filled pilot balloons (pibals) with two theodolites. The theodolites were separated by an east-west baseline distance of about 1.4 km and synchronized readings (azimuth and elevation) from each theodolite were made every thirty seconds, corresponding with an incremental balloon height rise in still air of about 65 m. In clear conditions, balloons were tracked for up to twenty minutes to an altitude in excess of 2 km. A time-height cross section of the relative streamlines $\psi(x, z)$ = constant in a plane normal to the surface front is shown in Fig. 18. These are determined by integrating the formula

$$\frac{\partial \psi}{\partial z} = u(x, z) - c, \qquad (1)$$

with respect to z, $u(x, z)$ being the horizontal wind component in the x-direction, normal to the surface front, with x and u positive in the direction towards the cold air, and c is the disturbance propagation speed in the x direction, equal to -13.2 m s^{-1}. In Fig. 18a, ψ is calculated from integration of Eq. (1) assuming that u is measured at a fixed x, equivalent to ignoring the sloping trajectory of balloons relative to the moving disturbance. To take the sloping balloon trajectory into account requires that the ascent rate of balloons relative to still air is known as described by Smith and Morton (1984; see appendix). The streamlines computed by integrating Eq. (1) along the sloping balloon trajectory $x = x_b(z)$ are shown in Fig. 18b for the region surrounding the frontal nose where errors in the simpler

TABLE 2. Temperature changes (°C) in the postfrontal air on 25 November 1982 and the maximum postfrontal wind gust (m s^{-1}) within one hour of the front.

Location	Maximum gust (m s^{-1})	Front arrival time (EDST)	Change in temperature (°C) within the given period (min) immediately following the front: 10	30	60
Nowra	18.5	1342	−18.0	−20.0	−21.2
Sydney Airport	24.7	1550	−18.0	−19.0	−20.0
Richmond	22.7	1722	−17.0	−18.7	−20.0
Williamtown	21.1	1823	−15.0	−16.3	−16.7
Coffs Harbour	15.4	0110*	+0.2	+0.4	+1.2

* The front reached Coffs Harbour on 26 November 1982.

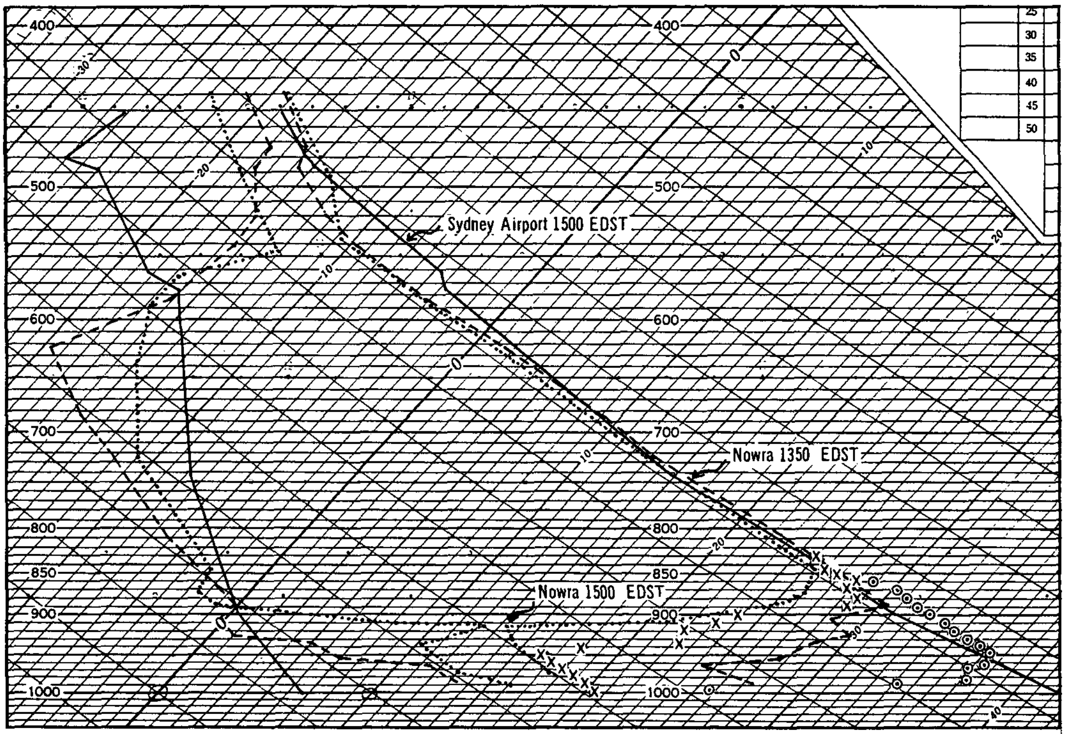


FIG. 13. Vertical temperature and dew-point soundings 1350 (dashed lines) and 1500 EDST (dotted lines) 25 November 1982 from Nowra, and at 1500 EDST (full lines) 25 November 1982 from Sydney Airport. Also shown are CSIRO aircraft temperature soundings in the warm air (circled dots) made between 1557 and 1603 EDST near 33°55′S, 151°45′E and in the cold air (crosses) made between 1529 and 1539 EDST near 34°40′S, 151°05′E.

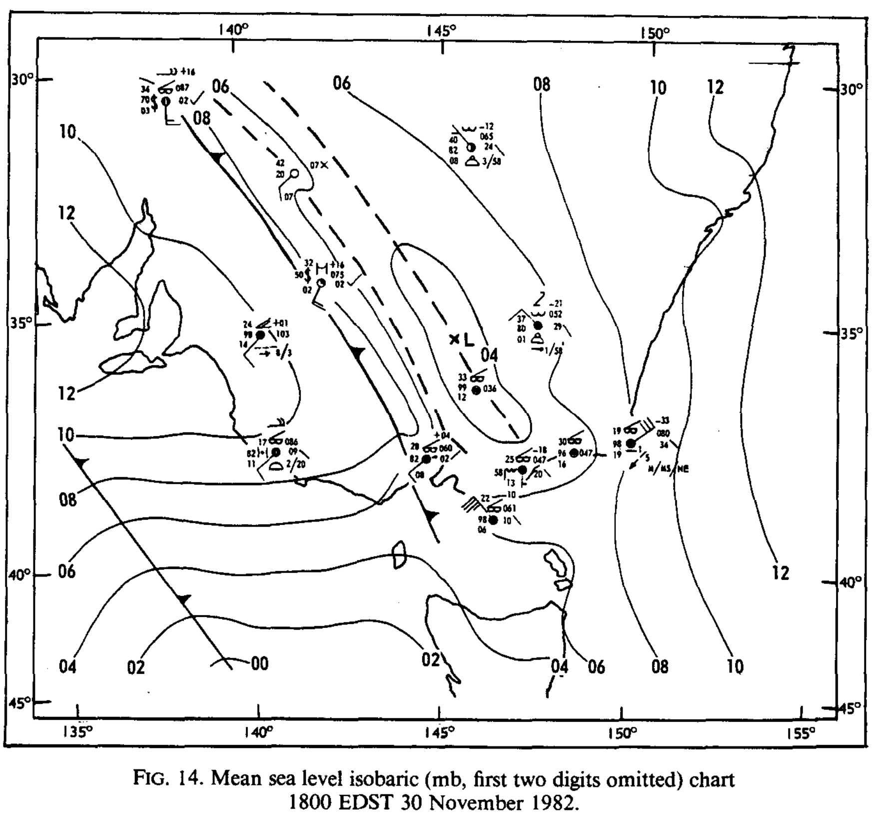


FIG. 14. Mean sea level isobaric (mb, first two digits omitted) chart 1800 EDST 30 November 1982.

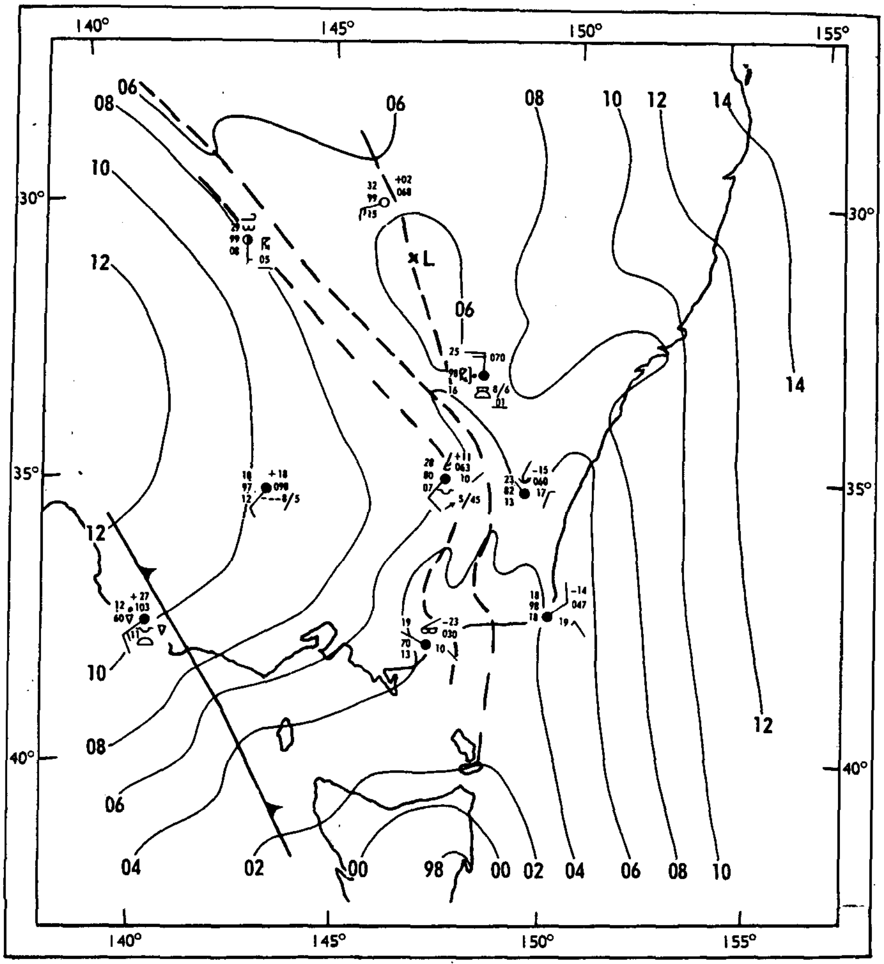


FIG. 15. Mean sea level isobaric (mb, first two digits omitted) chart 0300 EDST 1 December 1982.

calculation for Fig. 18a are expected to be most significant.

Both streamline patterns highlight the roll vortex nature of the frontal head with no low level feeder flow towards it. Comparison of the two streamline fields shows that the two small circulation centers in Fig. 18a should not be regarded as significant, but that the overall relative flow pattern is not sensitive to the method of calculating ψ.

4. Discussion

The event on 25 November 1982 could be described as a typical burster, because a marked increase in wind strength occurred as it moved northward. The increase in wind strength was due, at least in part, to the strengthening postfrontal pressure gradient. Maximum wind gusts were stronger on 25 November than on 1 December because of the stronger pressure gradients in the postfrontal air. The contribution of the horizontal advection of cold air below 850 mb to the pressure change can be deduced using the Nowra temperature and dewpoint soundings and the hydrostatic equation. Table 4 shows the surface pressure changes calculated with the assumption of constant height for the 850 mb surface. The differences between calculated and measured changes reflect, of course, the actual change in the 850 mb height, and show that on 25 November there was a significant lowering of the 850 mb pressure level. Without this there would have been a significantly larger surface pressure rise, i.e., 3.9 mb as opposed to 2.6 mb. In contrast, on 1 December, cold air advection below 850 mb accounts for virtually all of the surface pressure increase.

The larger pressure increase due to the horizontal advection of cold air during the 70 min between soundings on 25 November was associated both with the greater density difference between the pre- and postfrontal air and a steeper frontal slope. The approximate slope on 25 November, assessed from the Nowra temperature sounding at 1500 EDST and the surface position of the front at this time, at an equivalent distance inland, was 1:27. The slope on 1 Decem-

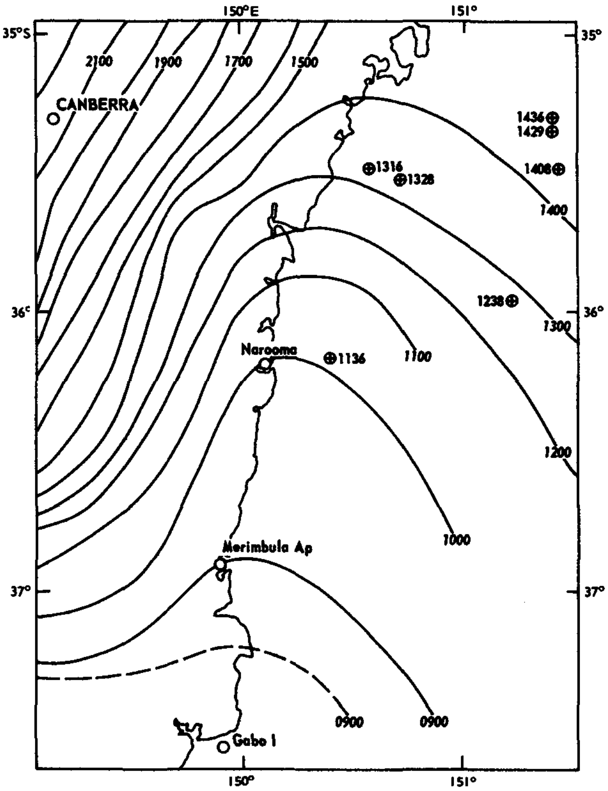


FIG. 16. Isochrones showing positions of the leading discontinuity (full lines) between 0900 and 2200 EDST 1 December 1982. Also shown (dashed line) is the position at 0900 EDST of the windshift line which caused the one discontinuity at Green Cape. Front locations over the ocean, determined by CSIRO aircraft, are shown with a circled cross and the times of location (EDST) are indicated.

ber was 1:62. These are in good agreement with the aircraft observations over the ocean (Coulman *et al.* 1985). Visual observations indicated much greater slopes near the heads of both fronts.

The highest burster translation speed on each day coincided with the greatest temperature difference across the front. Coulman *et al.* discuss this and the effects of density difference and layer depth in more detail on the basis of the aircraft soundings. In addition to the temperature or density difference across the front, the depth of the cold air has an effect on the burster propagation speed. The decreases in speed as the fronts move inland from the New South Wales coast, shown in Figs. 8 and 16, can be partially attributed to the decrease in the depth of the cold air at the head of the burster due to an increase in terrain elevation. Turbulent and convective mixing would tend to offset this change in depth. A weaker density difference across the front would contribute to its deceleration.

In view of the difficulty of forecasting the evolution of southerly bursters from synoptic data it is interesting to make a comparison between the output of the MFM model of Gauntlett *et al.* (1984) and the verifying MSL analyses as shown in Fig. 19. The model is a ten-layer, hydrostatic, 60 km primitive equations model which includes an efficient semi-implicit time differencing algorithm, has an option of a vertical mode initialization procedure and incorporates realistic topographical forcing. Figures 19a and 19b are, respectively, the model results and analysis at 2100 EDST 25 November 1982, and Figs. 19c and 19d the model results and analysis at 2100 EDST 1 December 1982. The model was run using operational data with no input of mesoscale analyses or satellite vertical sounding data. Prognoses are 24 hours in advance of the initial analyses. The 12 hour prognoses on both days (not shown) develop mesoscale lows which are much too deep and pressures which are lower than observed, particularly over the western half of the prognosis area. The 24 hour prognoses (Figs. 19a and 19c) both reproduce the blocking of the front by the mountains. However, the coastal positions of the front are well south of the actual positions as are the strongest postfrontal pressure gradients. The slow frontal speeds on the New South Wales coast can be particularly attributed to the model's inability to simulate the rapidly changing temperature gradient across the fronts. This is a consequence of the absence of a diurnal cycle of sensible heat flux. The latest fine mesh model overcomes this deficiency. Pressures on the prognosis for 1 December are up to 14 mb too low. The lower than observed pressures over mountainous terrain is thought to be due to deficiencies in parameterization. On both prognoses there is no ridge along the coast to the south of the front. Despite the limitations described, both MFM model prognoses give a much better representation of the MSL pressure distribution than the Australian Bureau of Meteorology operational prognoses. The MFM model accurately simulated most of the pressure distribution associated with the weak southerly change event on 7 November 1982; however, it positioned a low pressure center about 370 km too far east. The model was not run for the other four weak changes.

Colquhoun (1981), on the basis of anemograph data, suggested that horizontal roll vortices were present in the head of some bursters. The streamline analysis in Fig. 18 showing the presence of a roll vortex at the head of the burster on 1 December 1982 confirms their occurrence. The vortex is shown by Coulman *et al.* (1985) to be accelerating as it moves northwards towards Sydney. Accordingly, it must separate from the cold air and its lifetime presumably depends upon the warming of the prefrontal air during the day, followed by decay due to mixing. Some hint of such a separation is evident in the anemograph traces for the event of 20 November 1973 shown in Fig. 4 where a period of very light winds develops behind the disturbance as it progresses northwards and the period is longer at Williamtown than at Sydney further to the south. Calculations of the distances between common features, based on the time intervals between them and estimated frontal propagation speeds, also suggest larger values at Wil-

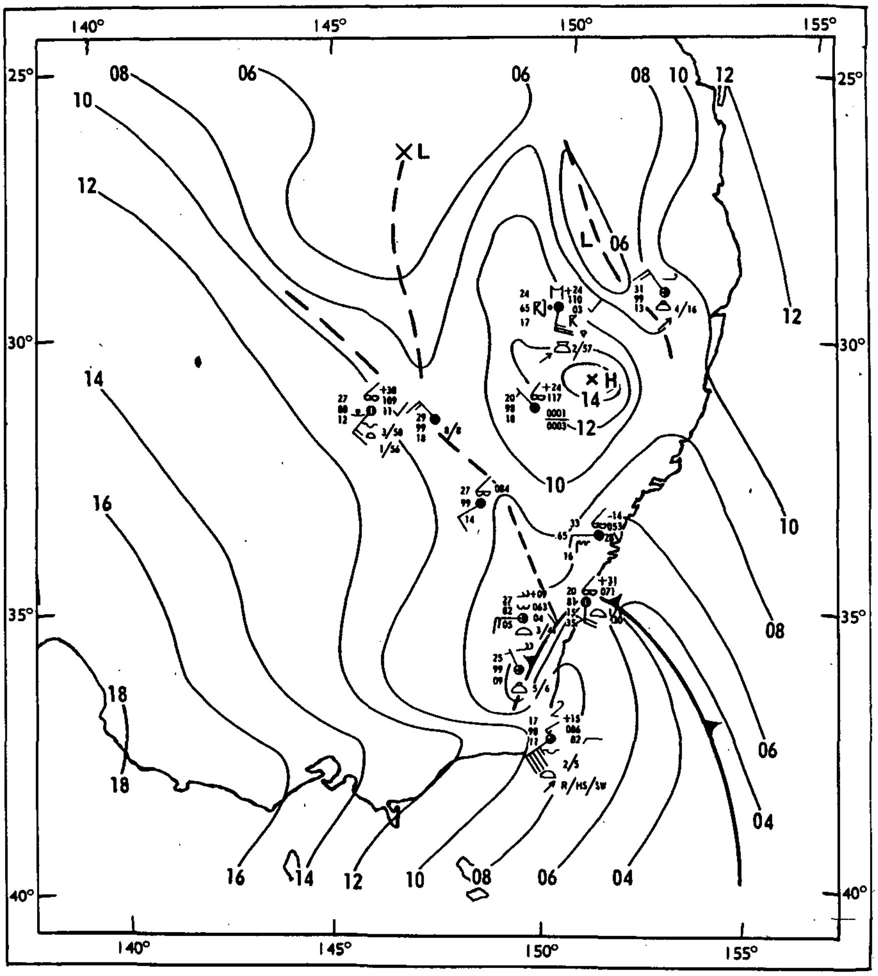


FIG. 17. Mean sea level isobaric (mb, first two digits omitted) chart 1500 EDST 1 December 1982.

liamtown. The existence of a roll vortex with lifetime governed by internal mixing has important implications for the ability to accurately forecast the onset and strength of the leading change and may partially explain the tendency of the MFM model to underestimate its speed particularly as the size of the closed circulation deduced from Fig. 18 makes this a subgrid scale feature.

The relative importance of synoptic and coastal forcing is difficult to determine. It is clear that many bursters develop because of land–sea temperature differences and hence have similarities with seabreeze fronts, and that others can develop from seabreeze fronts. These developments are dependent on the synoptic situation but their subsequent evolution may be at least partially independent of synoptic scale features. Diagnostic studies planned at Monash University utilizing the MFM model and a later mesoscale model should shed light on this issue.

TABLE 3. Maximum postfrontal wind gusts within one hour of frontal arrival time on 1 December 1982.

Location	Maximum gust ($m\ s^{-1}$)	Front arrival time (EDST)
Nowra	18.0	1445
Sydney Airport	21.1	1650
Bankstown	20.1	1653
Richmond	17.0	1748
Williamtown	18.0	1955
Coffs Harbour	10.3	0213*

* The front reached Coffs Harbour on 2 December 1982.

The importance of topography is demonstrated by Gauntlett *et al.* (1984) who show that when topography is removed from burster situations no burster is developed by the model. Coastline orientation must also affect burster characteristics such as the coastal acceleration when the prefrontal/postfrontal temperature contrast increases. If the Victorian coastline continued in an east–west direction making the Tasman Sea flat land a reduction would occur in this temperature contrast on the eastern side of the mountains producing values similar to those prevailing on the western side.

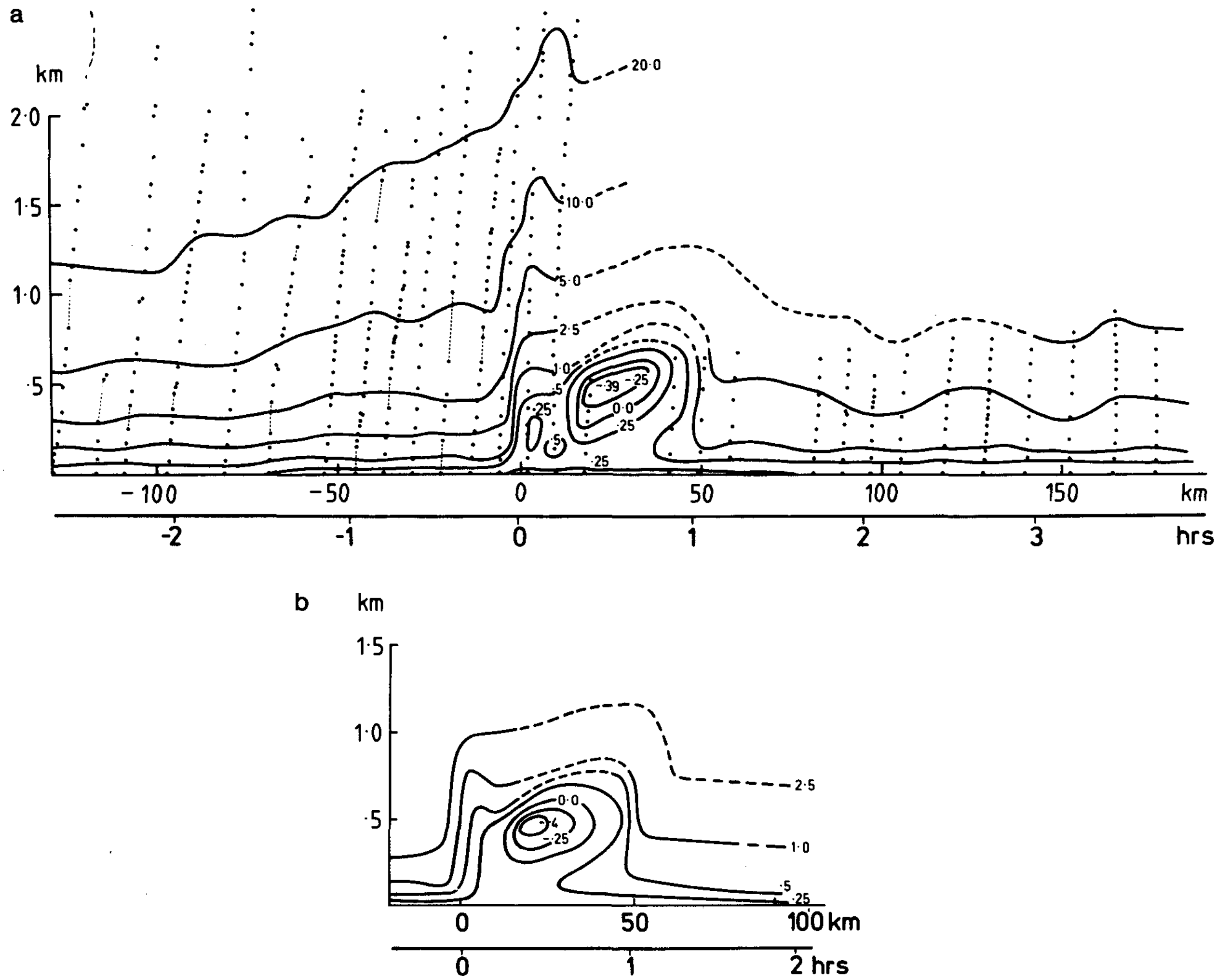


FIG. 18. Time–height cross section of relative streamline $\psi(x, z)$ in a plane normal to the surface front, on 1 December 1982 i.e., in the direction 175 deg. Time is measured relative to the onset time of the front (at 1448) and the time to space conversion assumes a uniform speed of translation c equal to -13.2 m s^{-1} (-*ve* means towards 355 deg), the speed of the front as it passed the sounding site near Nowra. (a) ψ computed assuming the relative balloon trajectories are vertical. (b) the streamlines near the head of the disturbance computed with the sloping balloon trajectories taken into account. In (a), dots indicate successive 30-second balloon positions relative to the disturbance front. In each case, streamlines are labeled in units of 10^3 m^2 s^{-1}.

Similar frontal velocities could be expected on each side of the mountains.

5. Concluding remarks

This paper gave details of a study of the synoptic aspects of strong southerly bursters and has described the evolution of two southerly burster events which occurred during a special observational period in November and December 1982. During this period, in addition to the routine synoptic network, a research aircraft, radiosonde soundings, serial pilot balloons and a network of anemographs were used to learn more

TABLE 4. Surface pressure changes in the postfrontal air derived from changes in the temperature and dewpoint soundings at Nowra assuming no change in the height of the 850 mb pressure surface, and actual pressure changes derived from the Nowra barometer readings at the time of the soundings.

Date	Time of frontal occurrence (EDST)	Sounding times (EDST)		Derived pressure change (assuming no change in surface to 850 mb thickness) (mb)	Actual pressure change (mb)
25 Nov 82	1342	1350	1500	+3.9	+2.6
1 Dec 82	1445	1515	1620	+1.8	+2.0

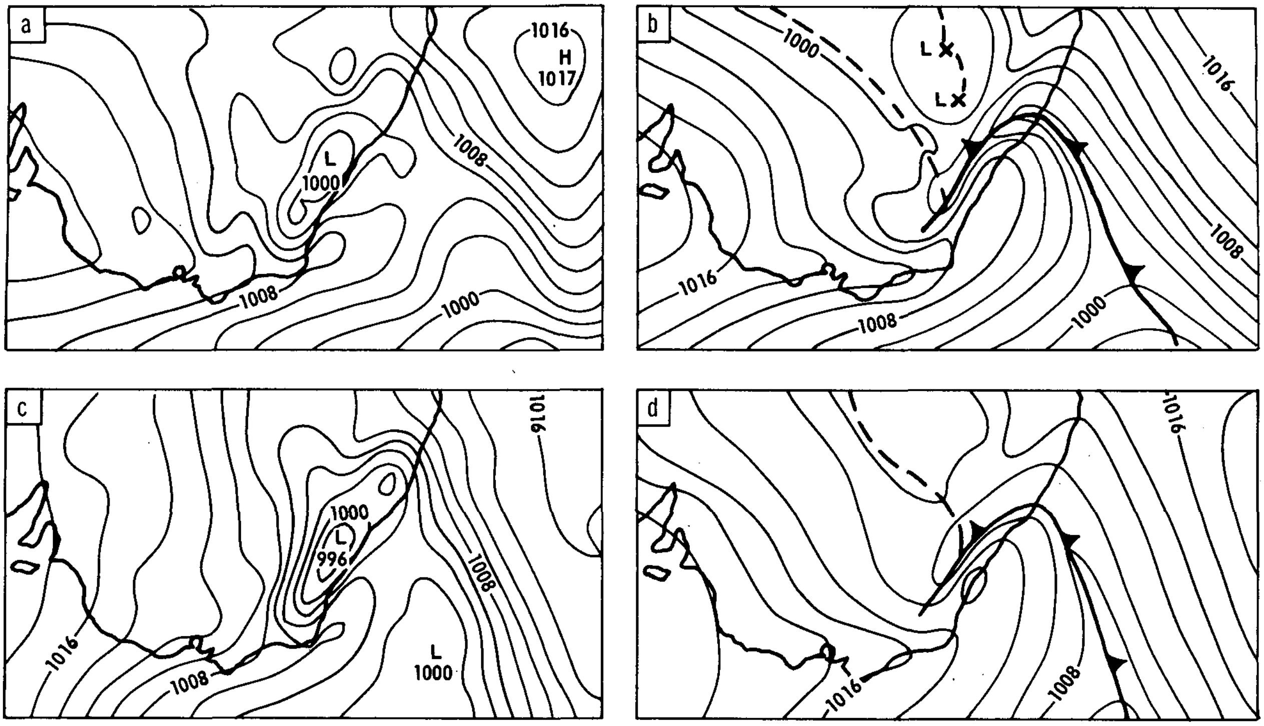


FIG. 19. Twenty-four hour MFM prognoses for (a) 2100 EDST 25 November 1982 and (c) 2100 EDST 1 December 1982 with the subjectively drawn analyses for the same times and dates (b) and (d), respectively.

about the structure and dynamics of bursters. Bursters have similarities with orographically trapped coastal fronts occurring on the eastern sides of South Africa, New Zealand, South America and North America. They also have features in common with an intense southward moving cold front on the eastern side of the Rocky Mountains which was described by Lilly (1981).

The topography of southeast Australia has a marked effect on the evolution of southerly bursters. The anemograph network used during SUBOP showed that the fronts advanced northward along the New South Wales coast at a much faster rate than their penetration inland. This feature and the observation that winds back as the fronts move inland must be kept in mind by meteorologists, especially when providing forecasts for personnel involved in forest fire control operations. The instability of the immediate postfrontal air is also of the greatest importance as it affects fire behavior by increasing both the buoyancy of fire plumes and the turbulence levels around the fire.

The serial pilot balloon soundings supported by aircraft data confirmed the existence of roll vortices in the postfrontal air. Their presence means that a knowledge of the translation speed of bursters and their postfrontal pressure gradients are not sufficient to determine the strength of postfrontal winds. Moreover, their possible effect on translation speed itself, coupled with their relatively small scale, has implications for the ability of current MFM models to accurately forecast frontal speeds. Translation speeds along the coast were found to be strongly affected by the local temperature, and hence density, difference across the front. Coulman *et al.* (1985) show that these speeds are well predicted by density current theory which incorporates this density difference and the depth of the cold air which has neutral stability. Successful operational application of the theory will necessitate accurate forecasts of these parameters.

The MFM model prognoses demonstrated an ability to provide much better prognoses than the current operational model, hence the potential to improve forecasting of burster events. Improvements are needed to better predict the frontal speed, the position of the strong postfrontal pressure gradient and pressures over elevated terrain.

Although two strong burster events occurred during SUBOP there was an absence of evening bursters, bursters associated with mesoscale lows, and those moving into, and displacing, a coastal seabreeze. A similar future program may present an opportunity to observe events such as these.

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