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Observations of a solitary wave train at Melbourne, Australia

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On the morning of 6 January 1984, a series of four roll clouds were observed propagating across Port Phillip Bay, Melbourne. Spaced about 6 km apart, the clouds were accompanied by regular oscillations in wind speed and direction and a sharp rise in surface pressure at the leading edge of the disturbance.

Analysis of surface and upper air data suggests the roll clouds were associated with a family of solitary waves which had evolved from a long wave perturbation of the nocturnal boundary layer, in accordance with nonlinear wave theory. A synoptic-scale trough accelerating along the southern Victoria coastline was probably the source of the perturbation.

Introduction

In a study of the summertime cool change of southeastern Australia, Berson et al. (1957, 1959) used the term 'change' to describe a sequence of discontinuities occurring within a few hours of one another. A backing of the wind, fall in temperature and rise in pressure were associated with each discontinuity, but the occurrence of precipitation was quite variable, with less than half the changes studied being associated with rainfall. More recently, publications from the Cold Fronts Research Programme (Wilson and Stern 1985; Garratt et al. 1985; Ryan and Wilson 1985) have discussed summertime cold frontal systems in terms of a frontal transition zone (FTZ) separating warm northerly winds from cool southwesterlies. The sequence of discontinuities discussed by Berson et al. lies within the FTZ, which is typically of the order of 300 km wide. Cool Southern Ocean air in the form of steady southwesterly winds lies behind the final discontinuity or line, which is usually referred to as the cold front and appears as such on weather charts. Discontinuities ahead of this line are termed prefrontal and examples include wind-shift lines embedded in a synoptic-scale prefrontal trough or induced by a wave travelling on an upper inversion (triggered perhaps by the following cold front) (Berson et al. 1957, 1959), and long-lasting squall outflows many kilometres from the original storm (Garratt et al. 1985). In this paper, a further type of prefrontal disturbance in the form of a solitary wave train is described.

At 0900 EDST* on 6 January 1984, a cold front was entering western Victoria. At the same time and 300 km ahead of the front, a spectacular disturbance in the form of four roll clouds (Fig. 1) passed through the Melbourne region. The leading edge of this disturbance was accompanied by a sharp pressure rise and shift in surface wind direction from north to south of west, with smaller oscillations in direction associated with each cloud band. Within an hour, the wind had returned to north.

Similar propagating roll clouds have been observed in association with an internal undular bore in the Gulf of Carpentaria region of northern Australia (Clarke et al. 1981; Clarke 1983). Known locally as the morning glory, this bore is created by the collision of east and west coast sea-breezes over Cape York Peninsula and propagates from the northeast on the stably stratified nocturnal boundary layer (Clarke 1984; Noonan and Smith 1986). Also observed in the region is a morning glory from the south, thought to be associated with a trough over central Australia (Smith et al. 1982). The cloud lines are a manifestation of solitary waves formed at the leading edge of the bore as it evolves with time.

Solitary waves have been studied extensively in central and northern Australia (Christie et al. 1978, 1979; Christie and Muirhead 1983) and observed in northwestern Australia (Smith 1986), western New South Wales (Drake 1984a) and South Australia (Drake 1984b). It is probable that a roll cloud observed by Robin (1978) over the waters of Spencer Gulf, South Australia was also caused by solitary wave activity (Christie et al. 1981) and more recently Clarke (1986) has interpreted roll cloud in the same region as being associated with a cold front assuming an undular bore-like character.

In the following section of this paper, the synoptic conditions under which the disturbance occurred are described. Mesoscale observations in the Melbourne region are presented next, followed by a summary of solitary wave theory and discussion relating to the waveguide and source of the disturbance.

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*EDST denotes Eastern Daylight Saving Time, which is 11 hours ahead of Greenwich Mean Time.

Fig. 1 Roll clouds at Aspendale on 6 January 1984. Photo looking towards the southwest taken by R. McVay.

The synoptic situation

The roll clouds of Fig. 1, and associated wind-shift lines, passed through the Melbourne region around 0900 EDST 6 January 1984. The MSL pressure analysis for this time (Fig. 2) shows an anticyclone in the Tasman Sea directing a northerly flow over Victoria. A cold front is about to enter western Victoria and a prefrontal trough is shown west of Melbourne, although the observations of the next section indicate its exact location may be further east. Such front-trough systems occur frequently in southern Australia during the summer months and the origin of this system can be traced as far as Western Australia.

Speed and orientation of the trough

Figure 3 shows the Victorian Regional Office MSL pressure analyses for 0300 EDST, 0600 EDST and 0900 EDST 6 January 1984. The speed (13.0 $\mathrm{m\,s^{-1}}$) and orientation (348°/168°) of the trough (dashed line in Fig. 3) have been computed from the times of the wind-direction shift at Adelaide (0000 EDST), Mt Gambier (0245) and Mildura (0705). When Cape Otway (0625 EDST) is used with Mt Gambier and Mildura, a speed and orientation of 15.3 $\mathrm{m\,s^{-1}}$ and 344°/164° respectively are obtained, indicating a greater speed for the trough in the coastal region than inland. This is suggested also by the 0600 EDST chart (Fig. 3(b)).

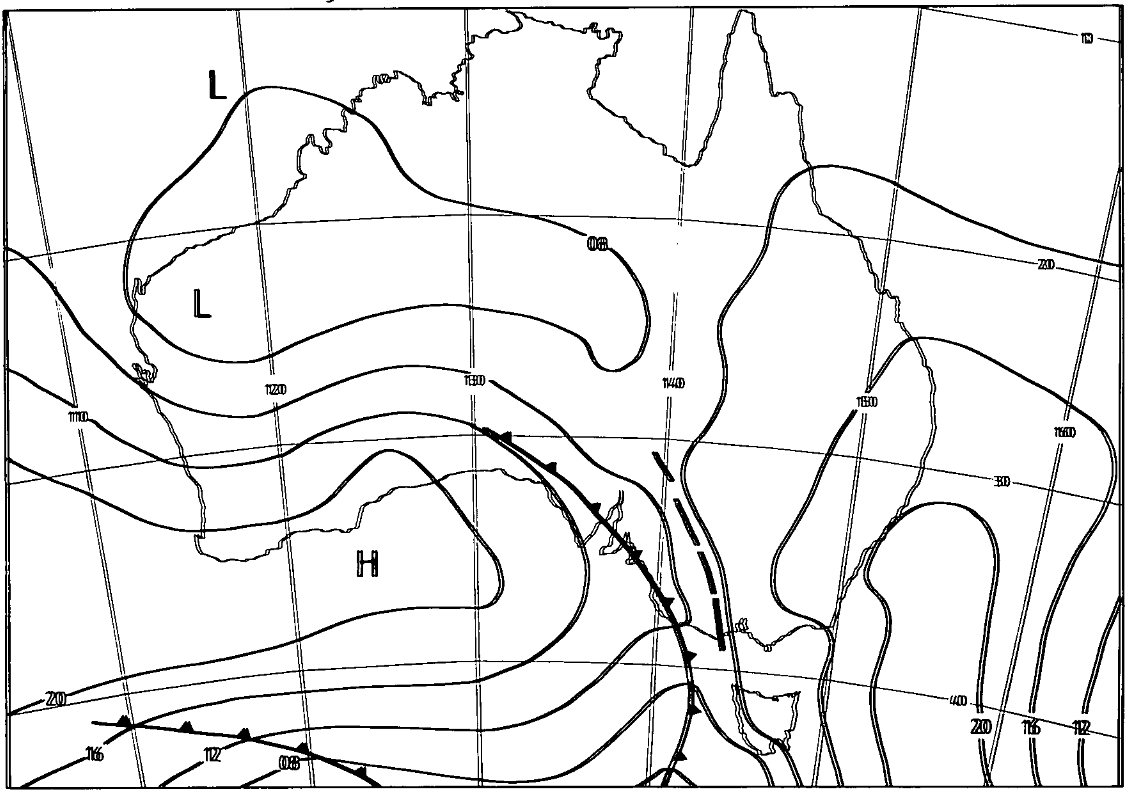
Figure 3(c) shows that the trough orientation in the coastal region changes markedly between 0600 and 0900 EDST, and this is confirmed by the mesoscale analysis for the Melbourne region (following section) where an orientation of 310°/130° is computed for travel between Point Henry (arrival time 0800 EDST) and the Melbourne Regional Office (0940 EDST). The trough accelerates between Cape Otway and Point Henry to a speed somewhere between 17.2 $\mathrm{m\,s^{-1}}$ (assuming orientation 344°/164°) and 19.8 $\mathrm{m\,s^{-1}}$ (assuming 310°/130°). Inspection of Mt Gambier wind and pressure traces and comparison of Fig. 3(c) with Fig. 2 indicates that the trough lying north from western Victoria in Fig. 3(c) is in fact the cold front and that the cold front indicated in Fig. 3(c) is fictitious.

Mesoscale observations

Isochrones

A sharp rise in pressure and sudden shift in wind direction from north to southwest were associated with the leading edge of the disturbance at Aspendale. The corresponding discontinuities on wind traces at other locations around Melbourne were then used to construct isochrones for the time of passage of the leading wind-shift line. A report of the roll clouds over Westernport Aerodrome, Tyabb (Mulroney 1984) at 0930 EDST was also used, under the assumption that the leading cloud was 10

Fig. 2 Mean sea level pressure (MSLP) analysis (Australian region) for 0900 EDST 6 January, 1984. Courtesy of Head Office, Bureau of Meteorology, Melbourne.



minutes behind the wind-shift line (see later). The isochrones are shown in Fig. 4 along with locations of anemometers.

On the western side of Port Phillip Bay, the disturbance was oriented 310°/130° and moved at 11.7 m s^{-1} between Pt Henry and Laverton, slowing to 6.1 m s^{-1} between Laverton and Essendon Airport. No perturbation of the surface wind field was detected at Tullamarine Airport 5 km northwest of Essendon, although a slight rise in pressure was observed. The change in orientation of the 0915 EDST isochrone on the eastern side of Port Phillip Bay is necessary to satisfy the time of sighting at Tyabb, but a gradual curvature was observed in the cloud bands at Aspendale and the orientation is consistent with the value observed at this location (325°/145°). However, as the passage at Tyabb was not recorded on any instrument, its timing and the resulting curve in the isochrones should not be given undue emphasis.

Surface observations

The wind signature of the disturbance at five locations around Port Phillip Bay is shown in Fig. 5. Periodic oscillations in speed and direction during passage, consistent with the observed wave-like nature of the cloud pattern, are discernible only in the traces from Pt Henry and Avalon. This aspect is discussed further in the final section.

At Aspendale, 5-minute readings of surface pressure (to the nearest 0.1 hPa) and a Woelfle anemograph trace were available, together with the author's notes. A sharp jump in pressure, on top of the usual semi-diurnal rise at this time of day, occurred at 0910 EDST, levelling out by 0925 EDST before commencing a steady fall at 1035 EDST (Fig. 6). A drop in wind speed and backing in direction also occurred at 0910 EDST, but by 0950 EDST the wind had resumed its northerly direction. Interestingly, the leading cloud band did not pass overhead until 0920 EDST when the wind was already from 190° (and possibly corresponds to its brief foray into the southeast quadrant). At this time the pressure had virtually reached its maximum value. Lack of cloud accompanying the initial wave has also been reported by Smith et al. (1982) for a southern morning glory at Burketown. The fourth cloud band dissipated before crossing the coastline and the rear

Fig. 3 Mean sea level pressure (MSLP) analyses (southeastern Australia region) for: (a) 0300 EDST 6 January, 1984, (b) 0600 EDST 6 January, 1984 and (c) 0900 EDST 6 January, 1984. Courtesy of Victorian Regional Forecast Office, Bureau of Meteorology, Melbourne.

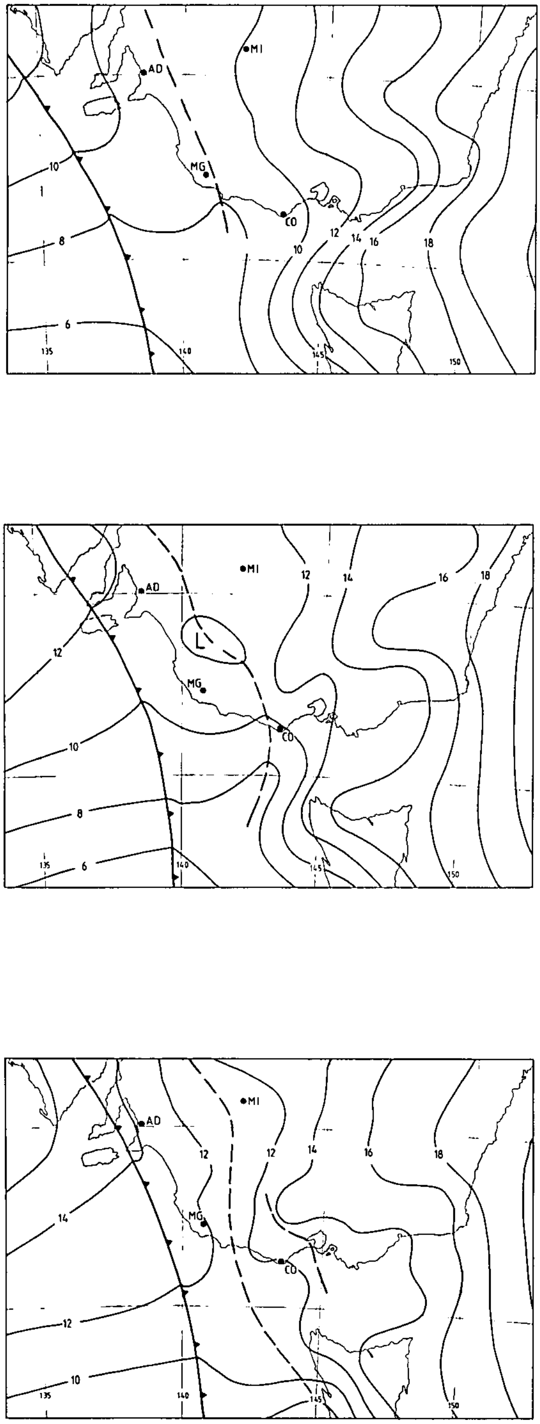


Fig. 4 Isochrones for the leading windshift line in the Melbourne region. Locations of anemometers used in the analysis are also shown.

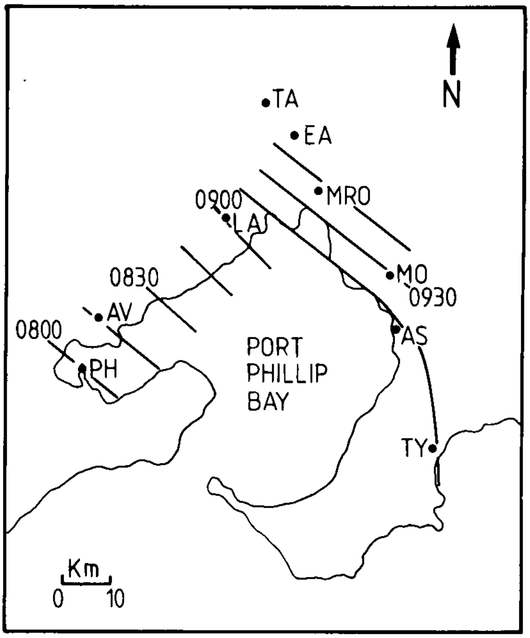
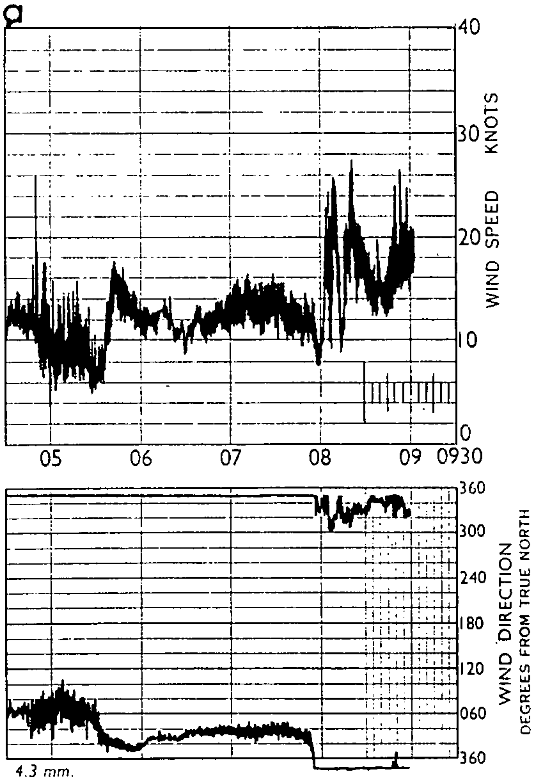
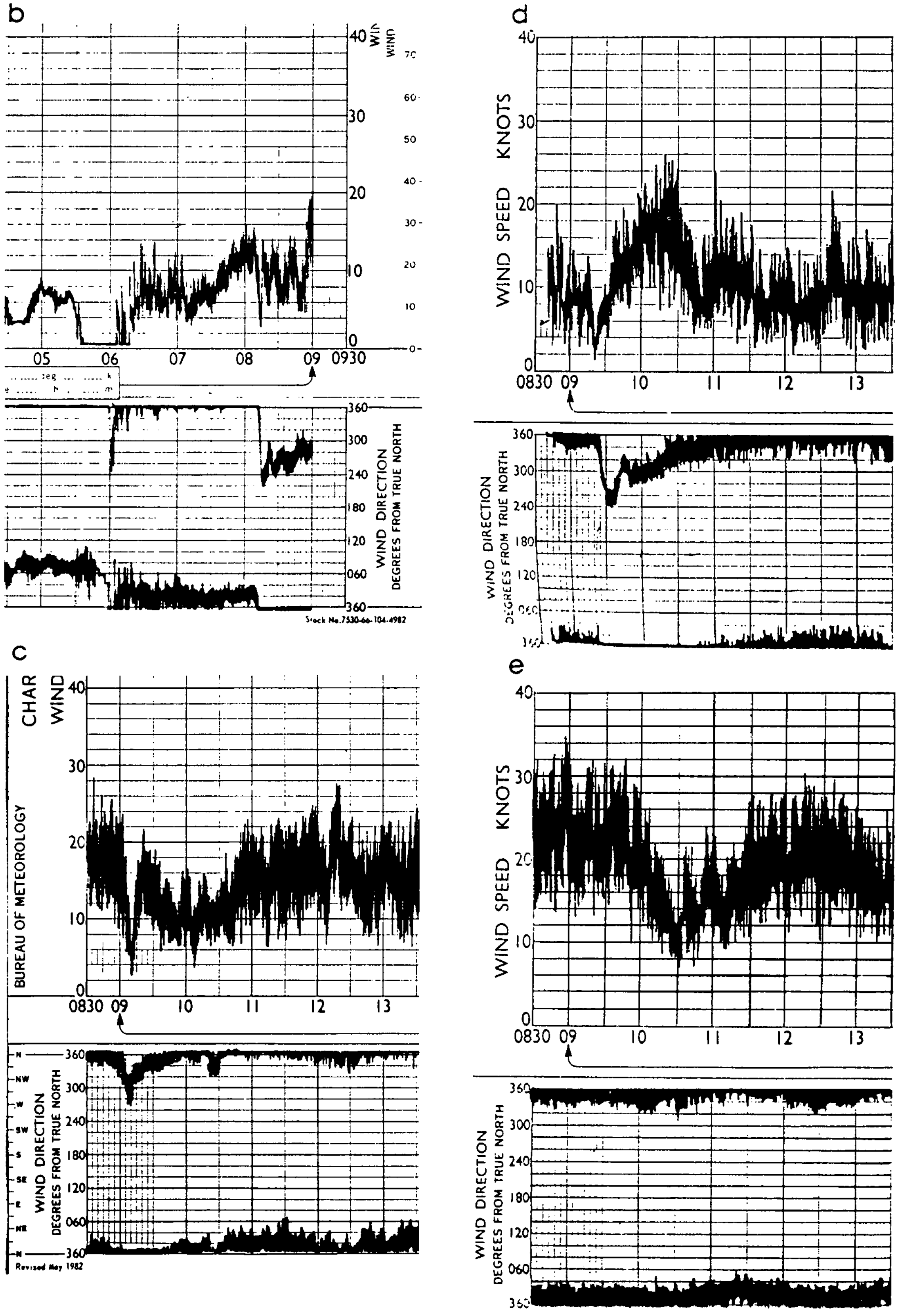


Fig. 5 Dines anemometer traces for: (a) Pt Henry, (b) Avalon, (c) Laverton, (d) Moorabbin and (e) Tullamarine Airport on 6 January, 1984. The wind speed scale is in knots and time is Eastern Daylight Saving Time.

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edge of the third band passed overhead at 0935 EDST. Thus the visible wave-like nature of the disturbance is confined to a fifteen-minute period (as indicated in Fig. 6), during which 5-minute readings of pressure were insufficient to resolve any wave structure. Oscillations of about 0.15 hPa amplitude do occur for a further 60 minutes, but are too weak to have parallels in the wind field.

Upper air observations

The only observations in this category for the Melbourne region are from the Laverton radiosonde flights at 2100 EDST 5 January (12 hours prior to the disturbance) and 0900 EDST 6 January (just after the disturbance). The evening temperature profile shows a shallow surface-based inversion developing beneath a daytime mixed layer capped by a subsidence inversion at 770 hPa (Fig. 7(a)). Air at all levels is very dry, increasing from 30 per cent relative humidity at the surface to 70 per cent at the subsidence inversion before sharply falling off to less than 20 per cent at higher levels. Winds beneath the inversion are in the vicinity of 10 m s^{-1} from north-northeast while above, slightly weaker north-northwesterlies prevail (Fig. 7(b)).

The 0900 EDST ascent (Fig. 7(a)) indicates a lowering of the subsidence inversion during the night to 815 hPa and a cooling below this level. The amount of cooling is greater than that due to radiational cooling alone, with the sustained pressure rise (Fig. 6) indicating cooler air was associated with the roll cloud disturbance (see 'Discussion'). Cold air advection throughout the night may also have contributed to the extra cooling. The dew-point trace indicates that the neutrally stable layer between 840 hPa and 820 hPa is cloud. According to the Laverton observers report, altocumulus and altostratus clouds with bases at 4000 m and 6000 m respectively were also in the vicinity, and this is consistent with the profiles of Fig. 7(a). However, these middle-level clouds had been reported since 0600 EDST and were not associated with the disturbance, which appears to have been confined below the subsidence inversion. Above the inversion, cooler moister air was advected into the region during the night.

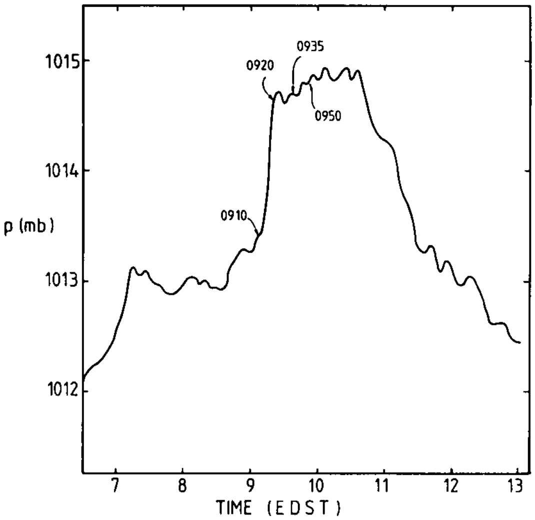


Fig. 6 Station level pressure trace at Aspendale 6 January, 1984.

Winds at all levels up to 400 hPa increased and backed with the approach of the cold frontal system. The strongest winds of 20 m s^{-1} were reported near the base level of the roll cloud (850 hPa) although the next reading was not until 750 hPa, well above the cloud top. The direction of the strong winds between 900 hPa and 750 hPa is parallel to the orientation of the disturbance at Laverton. The normal wind component at all levels is less than the propagation speed of the disturbance, illustrating its wave-like, rather than advective, nature.

Solitary waves in deep fluids

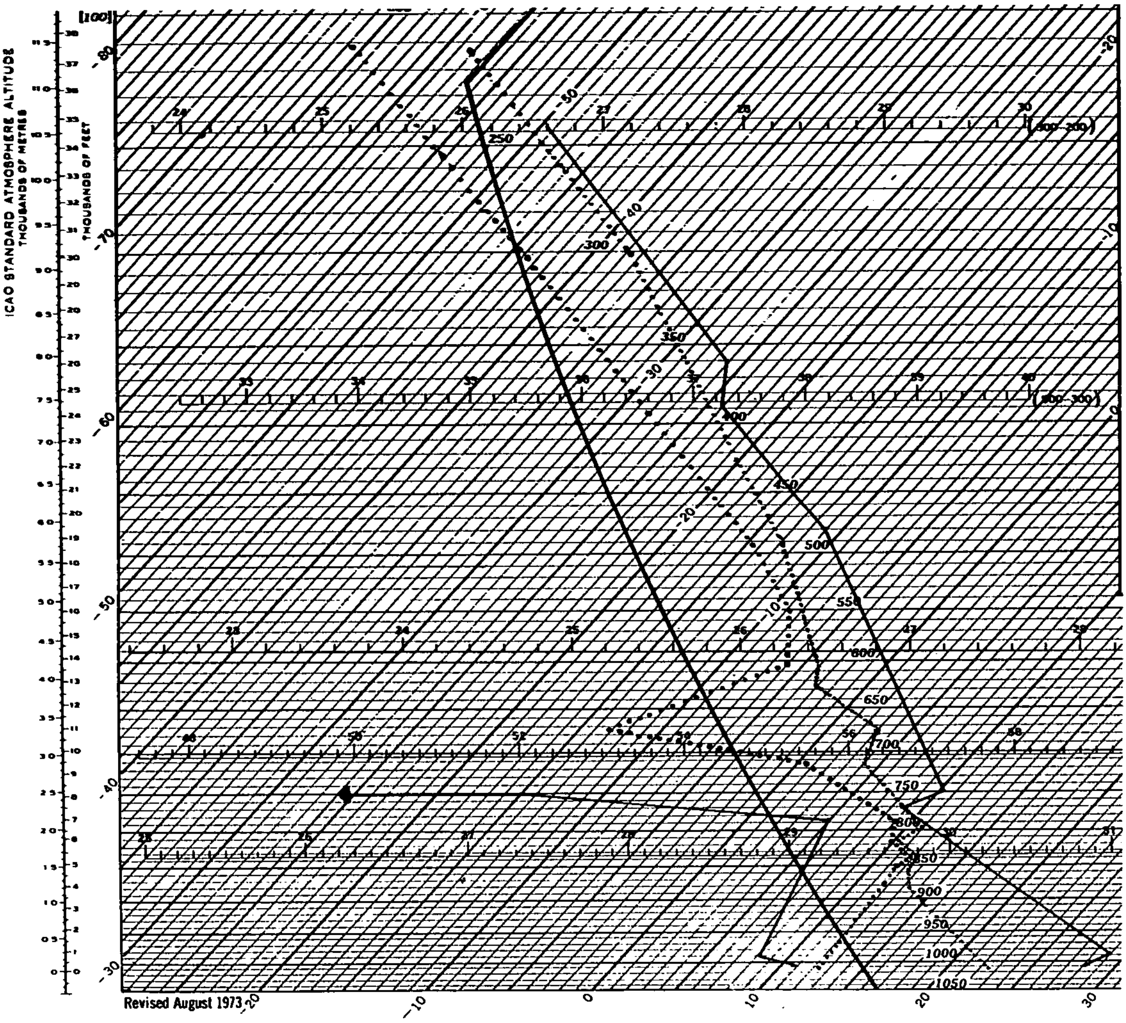
The observations indicate that the disturbance has the form of a wave train propagating on a low-level stably stratified layer, underlying a deeper less stable layer. This section briefly reviews the relevant theoretical and experimental studies relating to such internal wave motion in deep fluids.

A solitary wave can be defined as a single wave of elevation which propagates at uniform velocity and without changing form, this latter property arising from the competing effects of frequency and amplitude dispersion. Early theoretical studies considered the problem of internal solitary waves in fluids of finite depth, where the analyses were based on the assumption that the horizontal length scale of motion is long compared with the fluid depth (see for example Keulegan 1953; Peters and Stoker 1960; Benjamin 1966). Theoretical investigations into a new type of solitary internal wave able to propagate in a fluid of infinite depth were presented by Benjamin (1967) and Davis and Acrivos (1967). The latter authors also were able to produce experimentally solitary waves travelling on a stratified region of limited depth h between two 'infinitely' deep homogeneous fluids. The waves have a characteristic wavelength much greater than h, so are long waves relative to h, not total depth.

More recent theoretical developments include the provision for vertical shear in the stratified layer (Maslowe and Redekopp 1980) and the extension of the first order theory to second order, making it more relevant to some of the large-amplitude disturbances observed in the atmosphere (Grimshaw 1981).

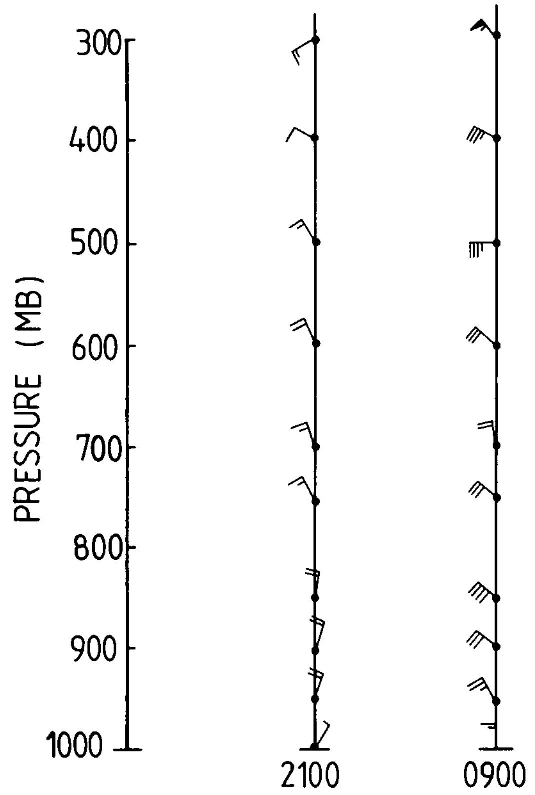
In the laboratory, Maxworthy (1980) was able to produce solitary waves by allowing a gravity current to move into a region of stratified fluid. The waves separated as they evolved from the leading edge of the gravity current and were ordered by amplitude,

Fig. 7(a) Temperature (°C) and dew-point (°C) profiles for 2100 EDST 5 January, 1984 (solid curves) and 0900 EDST 6 January, 1984 (dotted curves).



with fluid from the gravity current invariably trapped within the leading solitary wave. This fluid was ejected rearwards as the wave amplitude decreased to a critical value for which a recirculation region was no longer possible. An interesting finding from these experiments was Maxworthy's view that 'if a given physical system is capable of supporting solitary wave motions, then such motions will invariably arise from quite general excitations'. This observation is illustrated well by the numerical solution of the Benjamin-Davis-Ono (BDO) wave equation in which an initial long wave of elevation (i.e. an arbitrary long wave disturbance to a stratified fluid) evolves into an amplitude-ordered set of solitary waves followed by a weak dispersing wave train (Christie and Muirhead 1983). This paper, and an earlier one (Christie et al. 1978), contain excellent summaries of the properties of atmospheric solitary waves, based on data over the flat terrain of northern Australia.

Fig. 7(b) Wind profiles for 2100 EDST and 0900 EDST. A full barb represents 5 m s^{-1}, and a flag 25 m s^{-1}.



Discussion

Application of the BDO equation to the disturbance to predict speed and wavelength (as done with limited success for the morning glory by Clarke et al. 1981 and Noonan and Smith 1985) is not possible in this case as vertical profiles of wind and temperature just prior to passage are not available. However, it is possible to calculate the wavelength using a speed and passage time of each wave. In view of the curved isochrones, it is difficult to estimate a disturbance speed as it passed over Aspendale, but using an orientation of 325°/145° over the Bay, a value of 13.1 m s^{-1} is obtained between Pt Henry and Aspendale. The leading wave plus the three visible waves passed over Aspendale in 25 minutes, giving a total disturbance length of 19.7 km and thus wavelength of 6.6 km. (An orientation of 310°/130° would give a 5.9 km wavelength.) In comparison, the northern Australia solitary wave observations of Christie and Muirhead (1983) reveal wavelengths between a few hundred metres and 10 km and speeds between 6 and 16 m s^{-1}.

Waveguide

Solitary waves over land are usually observed during the night-time and early morning daylight hours as the stably stratified nocturnal boundary layer has been found to be an adequate medium for the propagation of these waves (Christie and Muirhead 1983; Drake 1984a). In coastal regions of northern Australia, the sea-breeze inversion can increase the stability of the nocturnally cooled layer (Clarke 1984; Physick and Smith 1985), while over the ocean a marine inversion arising from the offshore flow of warm land air over the cooler sea has been postulated as the waveguide for solitary waves observed off the coasts of northwest Australia (Smith 1986) and South Australia (Robin 1978; Drake 1984b).

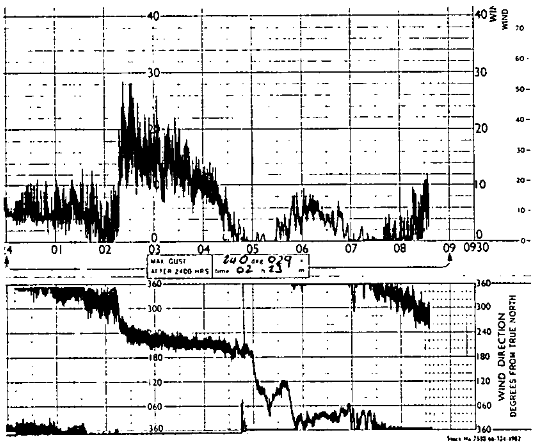
For the disturbance described here it is most likely that the nocturnal boundary layer over land (and in a modified form over the Bay) beneath the previous day's mixed layer of near-neutral stability provided the waveguide, although the subsidence inversion near 800 hPa (Fig. 7(a)) could also have supported the wave motion. However, the latter seems unlikely as: (a) the stable layer above this inversion would allow the vertical radiation of wave energy; and (b) the wave-like nature of the disturbance disappeared (visually at least) as the cloud rapidly broke up over land north and east of Port Phillip Bay, presumably due to destruction of the nocturnal inversion by convective heating. The lack of any perturbation to the wind field at Tullamarine also illustrates the rapid demise of the disturbance as it moved over the heated land. Although its dissipation is primarily due to the erosion of the low-level stable layer, a strong factor in the deceleration between Pt Henry and Melbourne was the opposing synoptic wind, which increased from 6 m s^{-1} from 20° at Avalon to 12 m s^{-1} from 360° at Tullamarine.

Disturbance source

Inspection of surface pressure traces between Adelaide and Melbourne reveals that the observed waves formed in the pre-frontal trough in Figs 3(a) to (c), although nowhere is the resolution of these barographs sufficient to indicate wave structure in the pressure field. Anemographs at Mt Gambier (Fig. 8) and Adelaide do not show the wave motion apparent in the wind field at Avalon and Pt Henry (Fig. 5), suggesting the waves developed between Mt Gambier (0245 EDST) and Pt Henry (0800 EDST). Only one cloud band was apparent at Ocean Grove (25 km southeast of Pt Henry) just prior to 0800 EDST (K. Wilson, private communication), although this fact may reflect the moisture distribution as much as the wave train's stage of evolution.

The higher pressure (Fig. 6) following the disturbance (maintained for 1.5 hours) indicates that the waves developed at the leading edge of a cooler air mass behind the trough, perhaps in the manner shown by Maxworthy (1980) in the laboratory. This air mass was not of synoptic dimensions, such as that normally found behind a

Fig. 8 Dines anemometer trace for Mt Gambier on 6 January, 1984. The wind speed scale is in knots and the time zone for Mt Gambier is 30 mins behind EDST. Note trough passage at 0215.



cold front, but had a horizontal scale of the order of 100 km. This distance is the mean of various locations and is obtained by assuming a steady translation speed for the duration of the high pressure anomaly.

Synoptic-scale troughs and fronts have been postulated as sources of solitary waves by Christie et al. (1981) and Smith et al. (1982). The latter authors suggest that the observed early evening acceleration of frontal troughs in central Australia could produce a perturbation of the nocturnal boundary layer which then evolves into the family of solitary waves observed the following morning in the Gulf of Carpentaria region (a southern morning glory). Clarke (1983) explained the evening trough acceleration, or surge, in terms of diurnal boundary layer processes producing a nocturnal jet which differs in strength and direction across the trough, while Smith et al. (1986) suggest that southerly disturbances might be generated also by interaction between the inland nocturnal jet and a southward-moving sea-breeze front.

The analyses of the section entitled 'The synoptic situation' show that trough acceleration takes place throughout the night (from a speed of 13 m s^{-1} at Mt Gambier to about 18 m s^{-1} between Cape Otway and Pt Henry), although it is not obvious why this should occur. One mechanism may be frontogenesis arising from synoptic horizontal shear acting on the north-south temperature gradient in the coastal region, a process which is investigated in the context of summertime cool changes by Reeder and Smith (1987). However, it appears that any frontal characteristics the trough may have acquired by early morning were quickly destroyed by diurnal heating and orography east of Melbourne, as there is no evidence of windshifts in surface wind traces after 1000 EDST at Tullamarine, Morwell or Sale, the latter two stations located 130 and 190 km east of Melbourne.

Concluding remarks

The limited data examined here indicate that a spectacular disturbance consisting of four long roll clouds over Port Phillip Bay was an amplitude-ordered solitary wave family, in agreement with general nonlinear wave theory for the evolution of an initial long wave of elevation. The nocturnally stratified boundary layer beneath the previous day's mixed layer of near-neutral stability acted as a waveguide, with an accelerating trough providing the long wave perturbation of this waveguide. Summertime troughs and fronts regularly traverse the southern Victorian coastline during the night-time, yet this is the first documented case of roll clouds in the region. However, if the clouds were absent, the oscillatory nature of this disturbance would have gone unnoticed as the conventional barographs in southern Victoria did not resolve the waves, and the wind oscillations would probably be noticed only by a researcher looking for such a signature. In fact, inspection of the Aspendale Dines anemometer records over the past six years reveals oscillatory wind behaviour associated with nocturnal troughs and fronts occurring at least twice per summer. It is suggested that the only unusual aspect of this disturbance was the moisture distribution in the Port Phillip Bay region which enabled clouds to form in the crests of the waves and disappear in the troughs, and thus make it visible to the casual observer.

Acknowledgments

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