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The influence of topography on Perth radiosonde observations

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Under strong synoptic easterlies, standard profile observations of temperature and wind, taken at the Perth radiosonde station, are shown to be influenced by wave effects induced by the Darling Scarp. These waves influence the profiles, in the lowest 2000 m, through the action of the wave in deforming the temperature and wind fields in the vicinity of the escarpment, or by the creation of temporally unsteady waves and eddies that can be periodically advected over the region.

Introduction

Perth, Western Australia, lies at 32°S 116°E on the relatively featureless Swan coastal plain, terminated to the east by the 300 m high Darling Scarp, about 20 km from the coast (see Fig. 1). This escarpment, which descends to the plain in 3 to 5 km, marks the western edge of an inland plateau and stretches for approximately 200 km in a north-south direction. The Perth radiosonde is released from Perth Airport, Guildford, approximately 7 km to the west of the escarpment (Fig. 1).

Under synoptic easterly flow, examples of extreme turbulence between 200 and 500 m have been noted in the radiosonde observations by Maher (1967). Southern and MacNicol (1973) also observed marked variations in the radiosonde's rate of ascent. Such deviations have been shown (Corby 1957) to be the result of wave effects which are caused by the forced descent of stable air layers over the escarpment. Waves occur under strong gradient winds, when the nocturnal inversion forms above a mechanically mixed layer. Mechanical forcing is an essential mechanism for wave effects (Klemp and Lilly 1975; Peltier and Clark 1979) whereas under weaker gradient flows, the mechanically enhanced bouyancy force is negligible, leading to katabatic drainage down the escarpment.

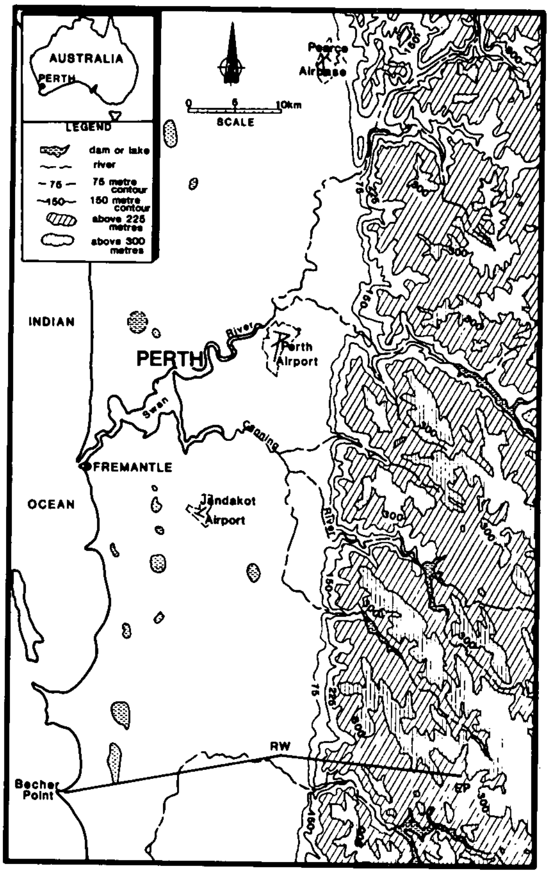
Although katabatic features have been observed extensively (e.g. Manins and Sawford 1979; Doran and Horst 1983), their interaction with moderate to high gradient winds is not fully understood. Through numerical modelling, Arritt (1985) has suggested that the two effects combine nonlinearly with the katabatic drainage acting to lower any gravity lee wave produced. However his simulations were limited to gradient winds of 3 m s^{-1} and assumed uniform temperature and wind profiles.

Thus under synoptic easterlies, the Darling Scarp has the potential to modify the observed temperature and wind profiles through both wave induction and/or katabatic drainage. Accordingly, the lower part of the radiosonde profile is unrepresentative of either the coastal plain or the undisturbed upstream conditions. This suggests that the sounding cannot be used in applications such as initialising numerical mesoscale models of the region or as a basis for defining mixing depths for air pollution modelling.

To ascertain the full extent of these effects, detailed profiles of temperature have been collected across the Swan coastal plain (Pitts and Lyons 1988) and compared with the corresponding radiosonde observations. In particular, this paper discusses observations made on representative days when the synoptic conditions led to easterly flow over the escarpment and atmospheric stability was conducive to the formation of topographical effects. We compare temperature profiles obtained on an east-west traverse across the plain, and specifically at Becher Point (26 km west of the Scarp, Fig. 1), Railway Line (3 km west of the Scarp) and East Point (on top of the Scarp), with the corresponding radiosonde observations.

Such a comparison assumes that the flow is essentially two-dimensional and steady state. The

Fig. 1 The Perth region, showing transect used for aircraft observations (RW, Railway Line; EP, East Point) and the location of airport meteorological stations.



two-dimensionality of the flow is evidenced by the close agreement found between the temperature and wind profiles, obtained from the radiosonde, and the corresponding isentropic surfaces, observed by the aircraft, some 45 km south. The steady state assumption is justified by the consistent observations reported by the aircraft over the two to three hours required to finish a complete traverse.

Observations and discussion

Under strong nocturnal easterly gradient winds, Pitts and Lyons (1988) observed the production of either hydraulic jumps, resonant lee waves or vertically propagating hydrostatic waves downwind from the escarpment. They noted that these phenomena could be differentiated primarily by the upstream temperature profile. In particular, a sharp inversion near the surface, with a near adiabatic layer above, produced a hydraulic jump whereas a stable layer aloft led to a vertically propagating hydrostatic wave. With a deep stable layer, the escarpment produces resonant lee waves which have been observed to extend 26 km to the lee of the escarpment.

Topographically induced waves have been reviewed by Smith (1979) and Klemp and Lilly (1980). The requirement for vertically propagating hydrostatic waves, or waves that are dominated by bouyancy forces is $u/Na < 0.1$, where u is the wind speed, N the Brunt-Vaisala frequency and a the half width of the terrain (Klemp and Lilly 1980). Vertically propagating waves are possible for larger values of this ratio, but the buoyancy force becomes less important as the ratio increases and the energy is progressively transmitted downstream through the generation of non-hydrostatic lee waves (Smith 1979).

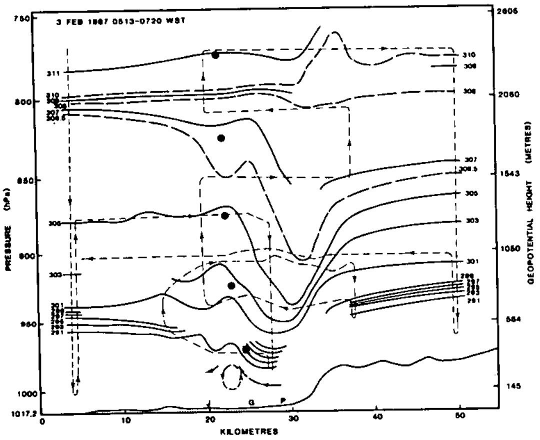
Hydraulic jumps occur when the flow at the ridge top is supercritical (Long 1954) with a near neutral layer above, restricting the vertical transmission of wave energy. Classical hydraulic theory requires a two-layer fluid to restrict this transmission of energy, although Smith (1985) and Smith and Sun (1987) suggest that the key element is the decoupling of the low-level accelerated flow from the undisturbed flow aloft. Under these conditions the flow accelerates down the escarpment and at some distance downwind becomes subcritical again through a turbulent jump.

Resonant lee waves occur when a stable layer exists in which buoyancy forces do not dominate. In this case, the wave energy is propagated to the lee of the escarpment. Such a condition is typified by the Scorer parameter, l ($l^2 = N^2/u^2 - u^{-1}d^2u/dz^2$), decreasing strongly with height and producing trapped or resonant lee waves. Hence the stable layer acts as a wave guide, as the decreased l above implies that the waves cannot be supported and thus are reflected.

Thus under strong easterly winds, substantial forcing and large amplitude waves can be produced by the Darling Scarp. As these occur in the vicinity of the radiosonde station substantial modification to the profile can be expected.

For example, at the time of the morning radiosonde release on 3 February 1987, an anticyclone situated to the south and a trough down the west coast combined to produce an estimated surface gradient wind of 15.6 m s^{-1} from 069° over the region, resulting in a strong vertically propagating hydrostatic wave tilted upstream from the escarpment (Fig. 2). Associated with the wave, there is a broad surface trough in the isentropes, approximately 7 km wide, with a rotor zone to the lee of the updraft region.

Fig. 2 **Cross-section of isentropes based on the aircraft observations for 3 February 1987. Large dots correspond to the approximate flight path of the radiosonde estimated from radar observations whereas the dashed line indicates the aircraft flight path. The relative locations of Jandakot (J), Perth (G) and Pearce (P) Airports are also shown.**



Assuming two-dimensionality of the flow, the radiosonde would be expected to have passed through this updraft region. Clearly under these conditions no single temperature profile is representative of conditions across the coastal plain.

Figure 3 illustrates that the lowest 2000 m of the radiosonde profile, taken at 0615 WST (Western Standard Time), is equivalent to the Becher Point observations and suggests the radiosonde passed to the lee of the trough associated with the hydrostatic wave. Above 2000 m the radiosonde profile deviates from the Becher Point results and is more representative of conditions upstream of the escarpment.

This agreement in the lowest 2000 m is consistent with the radiosonde track shown in Fig. 2, and supports the assumption of two-dimensionality of the flow. The radiosonde passed through the inversion at the crest of the first small wave above the rotor, having experienced, in the lowest 400 m, vertical velocities 1.5 m s^{-1} above those encountered elsewhere in the flight. Consequently, the agreement in profiles is based on the fortuitous track of the radiosonde in relation to the wave.

Radar observations of the radiosonde show an average wind speed of 24 m s^{-1} in the layer from 410-760 m (Fig. 4), compared to a gradient wind of 15.6 m s^{-1}, estimated from the surface pressure gradient. Assuming stationary flow undergoing only adiabatic processes, the isentropes of Fig. 2 represent streamlines. Thus the convergence of

Fig. 3 **Comparison of the radiosonde temperature trace with aircraft observed temperature profiles for 3 February 1987.**

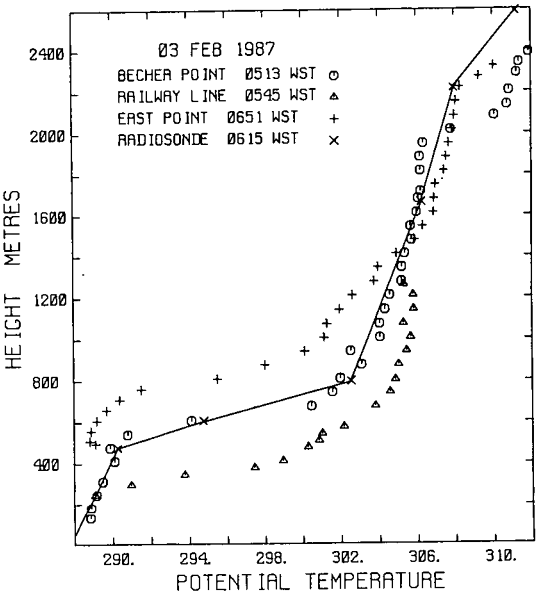
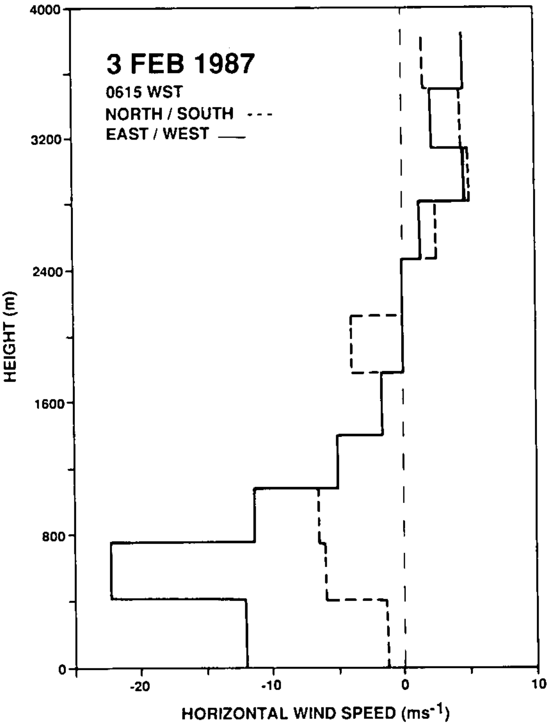


Fig. 4 **Observed profile of horizontal wind speed from radar observations of the radiosonde for 3 February 1987.**



the isentropes as the air flows over the escarpment is indicative of a speed up as the air flows towards the wave trough. A corresponding decrease in wind speed to the lee of the trough occurs with the divergence of the isentropes. The wave also produces turbulence which results in a weaker inversion downwind of the escarpment than upwind.

The synoptic condition on 21 January 1987 was dominated by ex-tropical cyclone *Connie* situated 750 km to the northeast and a high pressure ridge to the south, directing a surface gradient wind of 16 m s-1 from 095° across Perth. This flow led to the formation of a lee wave emanating from the escarpment (Fig. 5) with a maximum amplitude at approximately 1000 m. This maximum was associated with the stable layer, whilst below 600 m in the mechanically mixed near neutral boundary layer, there is little wave activity. Consequently one would not expect any deformation of the temperature or wind fields near the ground.

Figure 6 illustrates a marked difference between the radiosonde profile and those obtained by the aircraft. Such a difference is attributable to the lee waves observed where the radiosonde may have ascended through a crest with the plane descent through a trough. This would give an estimated crest to trough height of 250 m compared to the 204 m Pitts and Lyons (1988) obtained using the analysis of Corby (1957). Under these conditions the radiosonde profile is substantially altered and needs to be corrected for wave effects, as described by Corby (1957) and Andersen (1966).

Under strong gradient winds, topographically induced waves influence the radiosonde observations through two distinct mechanisms. Induced turbulence leads to a weakening of the inversion to the lee of the wave and deformation of the isentropes makes soundings to the lee of the escarpment unrepresentative of the general flow.

Fig. 5 **As for Fig. 2, but based on measurements for 21 January 1987.**

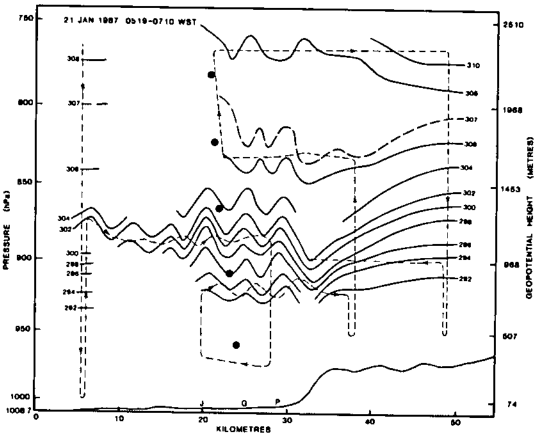
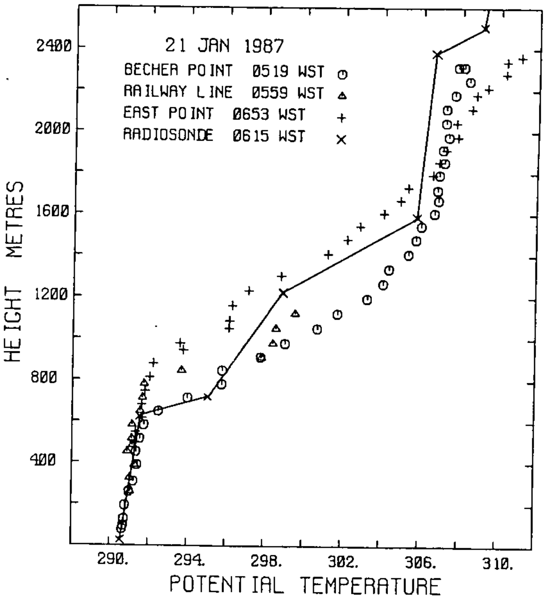


Fig. 6 **Comparison of the radiosonde temperature trace with aircraft observed temperature profiles for 21 January 1987.**



Under weaker easterly gradient winds, atmospheric flows can still be dominated by mechanically forced buoyancy effects provided that u/N << a (Smith 1979). However under these flows, the mechanical forcing over the surface roughness decreases and hence, the nocturnal radiational inversion tends to be closer to the surface. Also these easterly flows are typically shallow and the flow reversal aloft restricts the vertical propagation of energy. Consequently the flow perturbations tend to be weaker in both their vertical and horizontal extent.

For example, on 28 January 1987 a deep trough down the west coast and a high pressure system to the southeast resulted in a gradient wind speed of 9 m s-1 from 084°, turning westerly at approximately 1100 m. This led to a quasi-steady flow which at stages resembled a weak resonant lee wave (Fig. 7). The lee wave had a wavelength of approximately 2 km, decreasing rapidly with distance from the escarpment. A comparison of the aircraft observed isentropic cross-sections and the radiosonde profiles (Fig. 8) suggests that the radiosonde was unaffected by the wave. Under

Fig. 7 **As for Fig. 2, but based on measurements for 28 January 1987.**

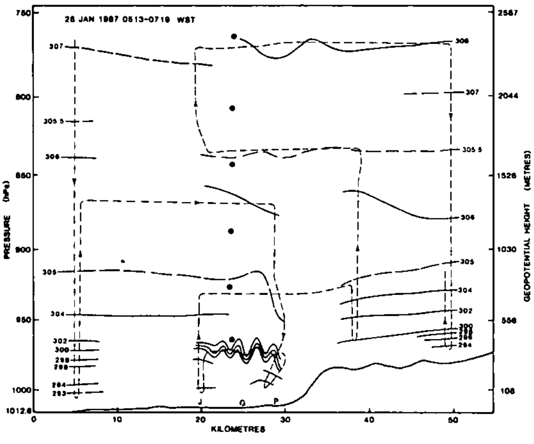
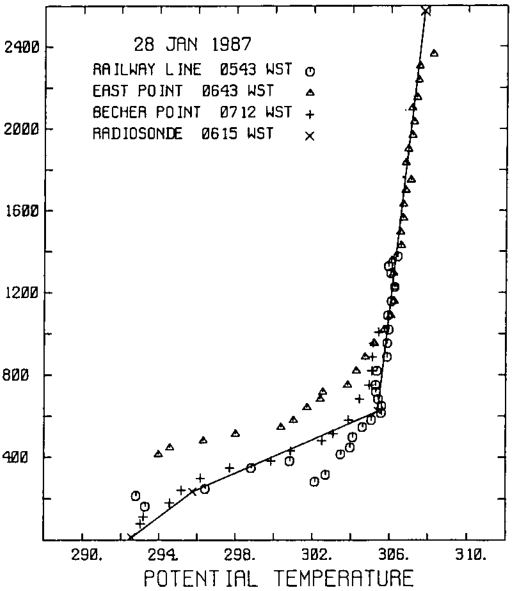


Fig. 8 **Comparison of the radiosonde temperature trace with aircraft observed temperature profiles for 28 January 1987.**



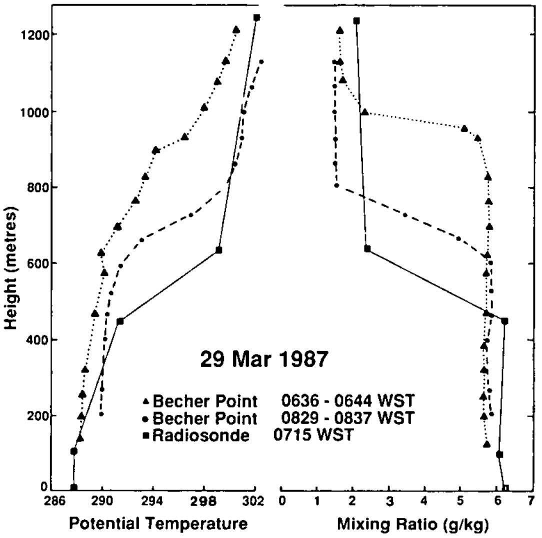
these lighter wind speed conditions, although topographically induced waves appear, they have less vertical and horizontal extent and hence less effect on the radiosonde profile.

However, a comparison of the profile below the escarpment with that above, illustrates that the inversion has become higher and weaker as the air flows over the escarpment. This weakening is associated with flow separation over the escarpment and appears to coincide with the height at which the synoptic scale wind turns to a westerly. A similar feature has been observed by Smith (1987) for the Yugoslavian bora. Hence the radiosonde profile is not representative of upstream conditions even under these lighter synoptic easterlies.

Unlike the previous days which were characterised by stationary synoptic situations, the surface gradient wind on 29 March 1987 was variable, increasing from 12 m s-1 to 19 m s-1 between 0000-0600 WST and then decreasing back to 14 m s-1 in the next three hours. This appears to have caused the amplification and subsequent rapid breaking of a wave system, as the anemometer at Guildford recorded an increase in wind speed from calm conditions to 12 m s-1, with gusts to 23 m s-1, in 2.5 hours, followed by a rapid decrease in wind speed to 4 m s-1 with marked fluctuations in direction. A similar feature was also observed at Jandakot, approximately 45 minutes later, suggesting a downwind movement of the wave phenomenon.

A comparison of temperature profiles taken at 0640 and 0833 WST over Becher Point (Fig. 9) shows the inversion has dropped by 250 m during that two hours, whilst the Perth radiosonde observed it even lower. As the radiosonde was

Fig. 9 **Comparison of aircraft observed temperature and mixing ratio profiles at Becher Point with the corresponding Perth radiosonde profile for 29 March 1987.**



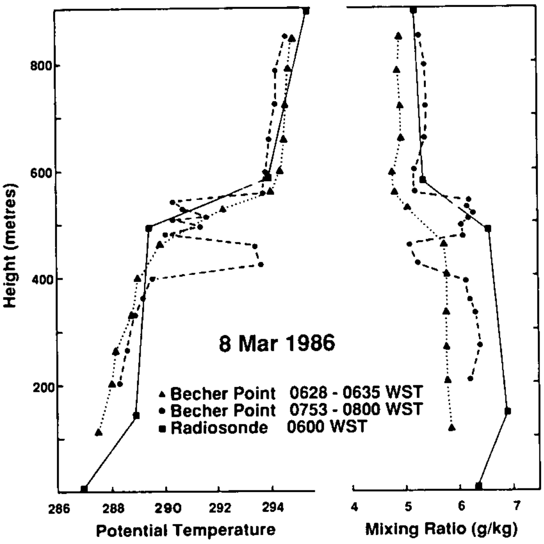
released at 0715 WST during the period of highest wind speed, it is possible that the balloon passed through the breaking wave.

A similar feature is evident on successive profiles taken over Becher Point on 8 March 1986. The first profile is representative of conditions at 0630 WST, whilst the second is representative of 0755 WST (Fig. 10). Although the first profile illustrates an inversion at 450 m, the second profile shows a large parcel of air with the characteristics of the air above the inversion displaced below the inversion. This parcel has been displaced by either rotor activity or wave breakdown. Thus even 26 km from the escarpment there are substantial transient effects on the observed temperature and wind fields produced by the escarpment.

Conclusion

These case studies highlight the influence of the Darling Scarp on temperature profiles observed from the Perth radiosonde trace. Although the escarpment is relatively insignificant physically, with a maximum height of 300 m, the strong persistent synoptic easterlies enhance its influence. During summer, synoptic winds above Perth are governed by the position of a subtropical ridge, which, combined with the formation of a heat trough down the coast, commonly results in easterly gradient winds of 10-20 m s^{-1}. As mountains with gentle windward and steep leeward slopes significantly enhance mountain waves (Lilly and Klemp 1979), these are ideal synoptic conditions for the establishment of topographically induced waves. The creation of turbulence and modification of atmospheric stability in the lee of the Darling Scarp means that under these conditions the Perth radiosonde trace is often unrepresentative of the coastal plain and the undisturbed flow upwind of the escarpment. As such it cannot be used as a representative profile to initialise regional mesoscale models, such as that described by McNider and Pielke (1981), which assume stationary homogeneous conditions for the initial profile.

Fig. 10 Comparison of aircraft observed temperature and mixing ratio profiles at Becher Point with the corresponding Perth radiosonde profile for 8 March 1986.



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