Summertime easterly surges in southeastern Australia: a case study of thermally forced flow

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During the summer of 1999/2000, wind profiling stations were operated at Wagga Wagga and Canberra Airports. Time series from the Canberra station clearly showed the passage of evening easterly surges. These surges were often observed to reach Wagga Wagga Airport about six hours later, around midnight. Data from the Bureau of Meteorology's observing network allow us to investigate the conditions under which these wind surges occur while the wind profiler data allow us to contrast their characteristics and vertical structure at the two stations. A three-day set of observations provides examples of surges that are driven by pressure gradients produced by differential heating; and for this period, our observations support earlier arguments that mesoscale forcing due to both the plateau effect and land-sea temperature contrasts are important in the development of these surges. At the same time, we argue that continental-scale thermal forcing associated with the development of the easterly inland trough, is important in driving the surges several hundred kilometres inland to Wagga Wagga. The contrasting case is when the inland trough dominates over the mesoscale forcing, and there are periods where the winds are easterly throughout the day. Under these conditions there is no night-time surge, and the nocturnal boundary layer is typical of summer in inland Australia, with the rapid acceleration of boundary-layer winds after dark and the development of a strong nocturnal jet.

Introduction

Cool, gusty, easterly wind changes often arrive in Canberra (35° 18.5´ S, 149° 12´ E, 576 m elevation; Fig. 1) late on summer afternoons, and are an important feature both locally and in the region to the east because they generally bring significant cooling and an increase in moisture. A particularly striking series of examples is shown in Fig. 2, which displays automatic weather station (AWS) records of temperature and dew-point temperature, pressure, wind speed and

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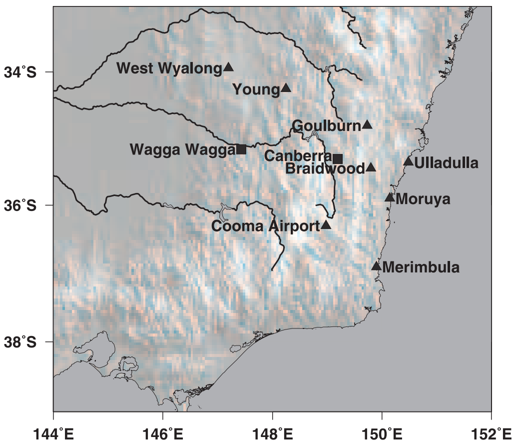
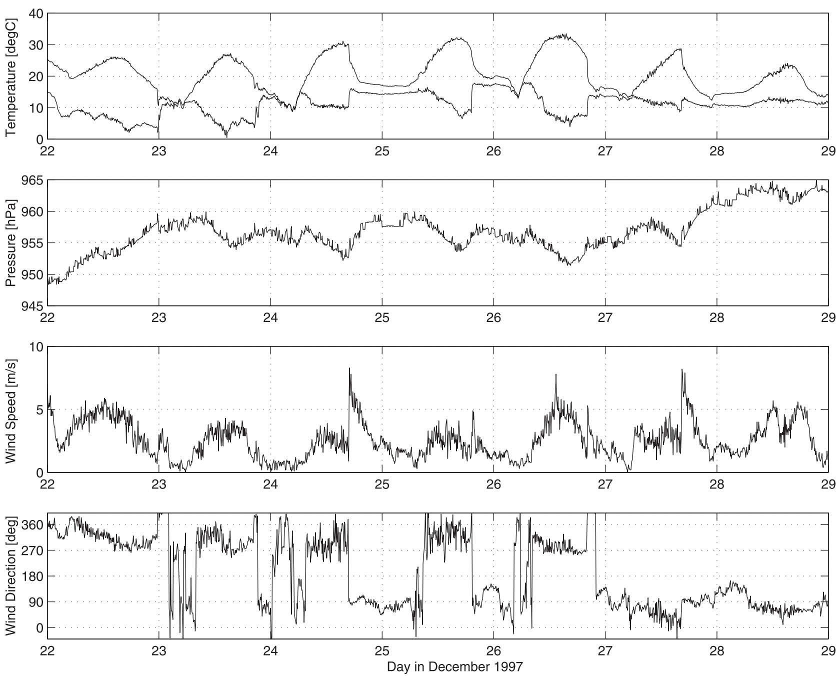
Fig. 1 Map of southeastern Australia showing wind profiler sites (squares) and Bureau of Meteorology AWS stations (triangles). Shading indicates height above mean sea level.



wind direction at the 2 m level for a week in December 1997. Over six consecutive days (22 to 27 December inclusive) there is a marked change to easterly winds and a drop in temperature, with an onset time generally in the late afternoon or early evening. Each change occurs within the six-minute averaging period of the AWS, and hence is clearly 'frontal' in character. Only after the change on the evening of 26 December is there a persistent shift in wind direction from the prevailing northwesterlies. This early set of observations initiated our interest in the problem of these easterly intrusions and the mechanisms which drive them much further inland than would usually be associated with sea-breezes.

The first scientific observations of these easterly changes in the Canberra region were by Clarke in the 1940s (Clarke 1983; Abbs and Physick 1992) who suggested that they were linked to the inland penetration of the East Coast sea-breeze. Clarke tracked the origin of these changes by taking temperature observations from a car and an aircraft. Subsequent numerical modelling and observations at other Australian sites, reviewed by Abbs and Physick (1992), show that the penetration of the sea-breeze to distances greater than 100 km from the

Fig. 2 AWS data from Canberra, 22–29 December 1997. Panels from the top are: screen temperature and dew-point temperature, station level pressure, 2 m wind speed and 2 m wind direction (origin of wind). Data are six minute average values; day marker indicates 0000 LT.



coast is not uncommon, and that the presence of a coastal range can enhance the apparent inland penetration of the sea-breeze (Clarke 1989). Similar surges have also been observed in locations such as the Iberian Plateau (Kottmeier et al. 2000), in the foothills of the Southern Alps in New Zealand (Kossmann et al. 2002) and the Kanto plain in Japan (Kondo 1990a, 1990b).

The afternoon easterly wind changes observed in Canberra are apparently similar to those observed in other locations around the world, but these changes also continue to propagate several hundreds of kilometres inland. Clarke (1983) described how easterly changes arrived in Wagga Wagga (approximately 320 km from the east coast) around midnight but he had only limited observations of the vertical structure of these intrusions at Wagga Wagga and the changes in their structure that had occurred as they propagated inland. Ground-based remote sensing instruments can now give wind profiles with both excellent time and height resolution. Further, with the enhancement of the Australian Bureau of Meteorology's surface network in the study region, it is now possible to investigate the prevailing local surface pressure field when intrusions occur. With these two sources of data we can gain greater insight into the intrusion or easterly surges than did Clarke (1983, 1989). In particular, Clarke's two and three-dimensional numerical modelling dealt only with idealised cases; in reality, the synoptic background seems to be critical to the formation and deep inland penetration of the intrusions.

Thus, in this paper, we present the initial results from the wind profiling instrumentation that was deployed in a four-month field experiment based at Canberra and Wagga Wagga Airports. We also focus on the insight into the easterlies that are evident from data from the Bureau of Meteorology's observing network. In particular, we highlight the different scales at which thermal forcing of the easterly flow can occur. This means that, far from being the dying remnants of sea-breezes when they propagate well inland (Clarke 1983, 1989), these easterly flows are, in fact, strongly forced systems. The next section outlines the instruments and observational program, while hypotheses regarding the forcing of the intrusions are discussed in the following section. The principal results are then presented in the form of two case studies.

Instruments and observing program

Instrumentation

The Lower Atmosphere Research Group, School of Physical, Environmental and Mathematical Sciences (PEMS), at the University of New South Wales at the Australian Defence Force Academy (UNSW@ADFA), operates a suite of instruments that comprise an integrated atmospheric observing system. The suite features three remote-sensing instruments with overlapping height coverage and varying range resolution: a 5 kHz sodar, a 1.875 kHz sodar, and a 1.275 GHz electromagnetic wind-profiling radar. All three operate on the same basic principle: transmit a pulse of energy into the atmosphere; detect the (range-gated) echoes from turbulence-generated refractive index fluctuations; extract the Doppler shift due to along-beam scatterer motion; and combine the Doppler shifts from three beams (one vertical, plus two inclined from the zenith and orthogonal) to compute the wind vector at each range gate. A more detailed description of these systems, including specifications, validation and intercomparison results, has been made by Taylor et al. (2000).

In addition to the wind data, the sodars give a qualitative picture of the distribution of turbulence microstructure (i.e. turbulent inhomogeneities), and hence the overall stability of the atmosphere. These sodar backscattering images are particularly valuable at night when the stably stratified nocturnal boundary layer usually lies entirely within the sodar height-range coverage, since under these conditions relative reflectivities can be directly compared and used to identify flow boundaries.

The synoptic data for the study came from *in situ* sensors in the Bureau of Meteorology's operational network: automatic weather stations (AWS), which record surface-level (1.5 m) pressure, temperature, humidity, and 10 m wind speed and direction; and balloon-borne radiosondes, which profile the same set of parameters during their 5 m s^{-1} ascent (equating to about ten minutes to rise through 3 km).

Wagga Inland Fronts Experiment (WIFEX)

During the summer of December 1999 through March 2000, a program of observations was carried out in central southeastern Australia (Taylor et al. 2000). The central observing station was at Wagga Wagga airport (35°9.9´ S, 147°28´ E, 212 m elevation) where a complete instrumental suite – comprising both sodars, the wind profiling radar, and an AWS – was installed, co-located with a Bureau of Meteorology radiosonde launching station. The secondary observing station was the Majura Valley field site in Canberra (about 2 km northwest of Canberra Airport, 35°18.5´ S, 149°12´ E, 576 m elevation), with a 1.875 kHz sodar and an AWS. A number of other Bureau of Meteorology AWS ground stations were identified, in order to provide timing and spatial coherence information. In this paper, we group the AWS stations into three categories: the 'coastal' stations of Ulladulla, Moruya and Merimbula; the 'tableland' stations of Goulburn, Braidwood, Canberra and Cooma; and the 'slopes and plains' stations of West Wyalong, Young and Wagga Wagga. Figure 1 depicts these sites in relation to the south-eastern Australia study region. Throughout this paper, local time (LT) is Eastern Standard Summer Time (ESST), which is UT + 11 hours.

Forcing mechanisms

Mesoscale thermal forcing: the plateau effect and sea-breeze

It is well known (e.g. Whiteman 2000) that the high terrain side of an escarpment acts as an elevated heat source to generate a diurnal circulation (the plateau effect). In simple terms, the solar heating of elevated terrain expands the air column above and results in an increase in the height of any given pressure surface. The horizontal pressure gradient resulting from the slope in these pressure surfaces drives an initial elevated outflow from the plateau. As a result of this mass transfer, a reverse near-surface pressure gradient develops which drives a low-level flow onto the plateau. The mechanism is essentially the same as that which results in a sea-breeze circulation. During the night, the reverse process generates downslope flows, although the nocturnal flows are not as deep because the heat fluxes are smaller and the vertical transport of momentum in the circulation is limited by the stability of the boundary layer. In the Australian east-coast cases, the contrast in surface conditions between the moist, forested coastal escarpment and the drier tableland woodlands results in an additional horizontal gradient in sensible heat flux which should enhance the plateau effect. Variations in cloud coverage between coastal and inland regions could also contribute to differential heating on the mesoscale.

Flows of this type are forced semi-diurnally. In mid-latitudes the period over which a flow will adjust towards geostrophic equilibrium (given that they are well-damped by convective turbulence) is the inertial period $2\pi/f$, where $f = |2\Omega\sin\phi|$ is the absolute value of the Coriolis parameter given the Earth's rotation rate Ω at latitude ϕ. For the latitudes of the present study the inertial period is about 21 hours, much longer than the forcing period. Hence, the Coriolis force should play only a secondary role in the dynamics of the intrusive flows associated with the low-level part of the plateau circulation. The dynamics of these flows will be governed by the interplay between pressure gradients (buoyancy), inertia and turbulent vertical momentum transport.

In situations where the coastal plain is relatively narrow (like the east coast of Australia) it is clear that there can be an interaction between the sea-breeze and plateau effect circulations. Thus, numerical studies of the inland penetration of the sea-breeze have reported that without the inclusion of topography and the resulting plateau circulation, many observed features of 'sea-breezes' are not well reproduced. Clarke (1989), after modelling the Goondiwindi breeze of near-coastal Queensland (315 km inland, and downwind of a 600 m elevation range some 100 km inland), noted, 'It is surprising that the presence of high ground strengthens and hastens the onset of the surge, rather than inhibiting it'. His model clearly showed the development of two cells: the inland one associated with the elevated heat source on the inland side of the dividing range; and a coastal or sea-breeze cell. As the cells developed they lost their separate identities, so that, in the sense that air from the coastal cell was entrained into the plateau cell, the inland propagating surge could be termed a sea-breeze. In their consideration of the sea-breeze propagating across the Kanto Plain of Japan towards the nearby 2000 m elevation mountain range about 100 km inland, Kikuchi et al. (1981) found that, 'the simulated wind systems are in better agreement with the observation in the mountainous case than in the flat case'. Kondo (1990a), investigating the same Kanto Plain feature, considered both 'without sea' and 'without topography' cases and showed how the actual resultant flow could be viewed a combination of a pure sea-breeze effect – or even a simple geostrophic – together with orographically induced differential heating, producing an 'Extended Sea Breeze'. Kondo (1990b) demonstrated both early acceleration and later deceleration of the flow as a consequence of topography.

A direct demonstration of the possible importance of the plateau effect came in a New Zealand study (Kossmann et al. 2001). Two-dimensional numerical simulations showed that the easterly surge in a coastal basin was mainly forced by the plateau effect. The cooling of the atmosphere by the sea-breeze enhanced the horizontal temperature gradient that exists between the air over the plateau and the plains, thereby increasing the intensity of the surge.

Synoptic-scale thermal forcing: inland heat lows

The greatest contrast between the eastern Australian case and some of the other locations reviewed is the effect of the large dry inland on the western side of the dividing range. This extended area of continental heating results in a much larger spatial-scale thermal forcing than result from the mesoscale effects reviewed previously. The average summer daytime mean sea-level pressure field across Australia is characterised by a broad band of low pressure in the northern part of the continent linked to troughs along the west coast and inland of the Great Dividing Range along the eastern side of the continent (Sturman and Tapper 1996). Hence, along both coasts there is an average cross-coastal (onshore) pressure gradient that will enhance any inland-directed flow. The nature of the circulation in this thermal low was demonstrated by the idealised model of Rácz and Smith (1999). Although the heating is modulated diurnally, the integrated energy input leads to a seasonal time-scale thermal anomaly that makes the continental heat troughs persistent features. Thus if there are periods where the heat low circulation dominates, Coriolis effects must be important, and the predominant flow (outside of the boundary layer) tends to lie along pressure contours; this is clearly demonstrated by the wind directions in the Rácz and Smith (1999) model. On the other hand, in the southeast of the continent the passage of synoptic-scale systems periodically disrupts the thermally driven circulation, so that near-geostrophic equilibrium is not obtained and the large-scale thermal forcing can contribute to unsteady flow down the pressure gradient.

Synoptic-scale dynamic forcing: fronts and coastal ridging

Across-range pressure gradients, favourable to inland flow, can also be set up along the east coast of Australia by synoptic-scale mechanisms. The most important of these follows from the evolution of cold fronts as they propagate across southeastern Australia. As a cold front reaches the east coast from the west, it tends to accelerate along the coastline as the cold air behind the front (to the southwest) is channelled along the coast beside the Great Dividing Range (Baines 1980). At the same time, the front is retarded on the western side of the range when the prefrontal north-westerly winds are partially blocked and forced south along the western side of the dividing range (McInnes 1993). These two factors combine to cause a characteristic s-shaped distortion to the front. In extreme cases, the frontal distortion evolves into a surge along the coast called a 'Southerly Buster' (Baines and McInnes 1997; Reid and Leslie 1999). Similar coastal wind surges occur on the east coast of New Zealand (Smith et al. 1991), South Africa and the eastern United States (McInnes 1993). This stretching and distortion of the cold front makes it possible for the changes to propagate through the Canberra region from the east. Further, the cooler air behind the front usually results in an along-coast ridge (Holland and Leslie 1986) and enhanced across-range pressure gradient.

Results

Overall forcing

It would be surprising if the pressure gradient across the east coast ranges did not have an important role in driving intrusions inland as far as Wagga Wagga. As an initial look at the background conditions to the intrusion phenomenon, we can examine the overall forcing for flow into the interior by examining the pressure gradient force. We use the mean sea-level pressure (MSLP) difference between Wagga Wagga and Ulladulla (a coastal station at almost the same latitude) as a proxy for the pressure gradient force and begin by considering the seasonal average. The summer mean diurnal pressure variation at the two locations is quite different (Fig. 3). For the summer period, Ulladulla showed an average daytime pressure variation of 2 hPa, in close agreement with the atmospheric tide at this latitude given by the Haurwitz expressions (Beer 1975). In contrast, Wagga Wagga had a mean peak-to-peak daytime variation very close to 4 hPa. Thus, even though the phase of the pressure signal is quite similar at the two location, the significantly greater amplitude of the daytime semidiurnal pressure variation inland means that, on average, there is a strong pressure gradient between the coast and inland (see Kong (1995) for a summary of Australia-wide trends in diurnal pressure variation). A maximum positive value (favourable to inland flow) of the mean Ulladulla to Wagga Wagga pressure difference occurs in the late evening (2000 LT). Interestingly, even though the average pressure at the two locations varies semidiurnally the pressure difference is clearly diurnal and this suggests very strongly that differences in daytime heating between the coastal and inland stations are responsible for the mean pressure differences.

As would be expected on the basis of the seasonal average, time series of hourly MSLP differences between Ulladulla and Wagga Wagga for each of the three months of summer 1999-2000 (Fig. 4) show a bias towards positive values, indicative of the overall importance of the interior heat low. Hourly pressure differences reach up to about 10 hPa, which is more than two times the summer average difference evident in Fig. 3. The expected diurnal variation of the pressure difference is superimposed on the longer period variations associated with the passage of weather systems. Diurnal thermal forcing results in a sharp increase in the pressure difference in the evening – a factor which is emphasised if a frontal passage has produced a significant local pressure-difference minimum – favouring the development of inland flow (17 and 18 December is a good example). An examination of sequences of MSLP charts for the period from the

Fig. 3 Mean diurnal variation in mean sea-level atmospheric pressure (MSLP) at (a) Ulladulla AWS (upper panel; hourly readings) and (b) Wagga Wagga Airport AWS (lower panel; half-hourly readings). The smooth curve is the 1999-2000 summer (December, January, February) mean, and means from the individual months are shown as: squares, December; diamonds, January; triangles, February. In each panel, the dotted curve with no data points is calculated by the Haurwitz expressions given by Beer (1975). Panel (c) is the difference between the Ulladulla and Wagga Wagga mean pressures. Circles show the hourly values and the curve shows the hourly values after a five-point smoothing filter has been applied. The method used to reduce the pressures to MSLP is discussed in Case II.

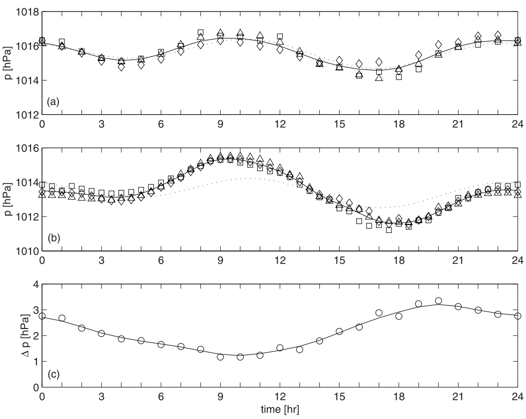
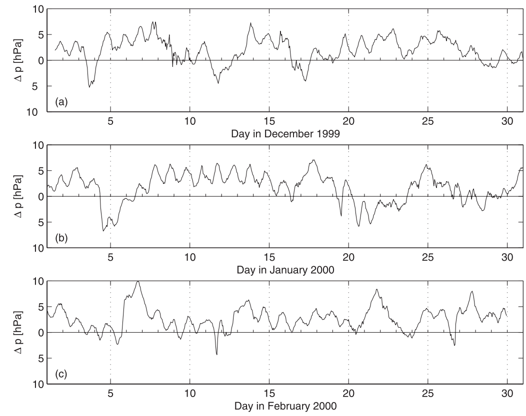


Fig. 4 Hourly differences between the mean sea-level pressure (MSLP) at Ulladulla and Wagga Wagga. Time series for (a) December 1999, (b) January 2000 and (c) February 2000. Day markers on the reference lines indicate 0000 LT.



Bureau of Meteorology's on-line chart archive showed that the passage of a front along the coast followed a period of reversed pressure gradient (i.e. higher pressure over the continent), followed by a rapid re-establishment of positive values due to the development of an east coastal ridge.

In the remainder of this section we focus on two case studies that emphasise the role of the two scales of thermal forcing mechanisms in the inland penetration of the easterly flow. At large scales we have the overall heating of the Australian continent, and hence the development of the continental heat low. On the mesoscale are the land-sea contrast and plateau effects included in the earlier idealised models and studies of Clarke (1983, 1989).

Case I: 8-15 January 2000 (sustained continental-scale thermal forcing)

One of the striking features of the pressure difference record (Fig. 4) is the period of strong diurnal pressure gradient, superimposed on a large positive mean pressure difference that occurred between 8 and 15 January 2000. This first case study illustrates what happens when continental-scale thermal forcing dominates. It is important to stress that between 8 and 15 January, even though the prevailing winds in both Canberra and Wagga Wagga for this period were easterlies, surge-like intrusions were not observed in either Canberra or Wagga Wagga. In fact, even the passage of a front to the south around 9 January did little to disrupt the situation. We note that the observed winds at Wagga Wagga compare favourably with the features of the idealised island heat low model of Rácz and Smith (1999).

With the long period of almost constant thermal forcing, the wind field adjusts to a balance between the pressure gradient, frictional and Coriolis forces (the latter due to the large spatial scales). Hence in Wagga Wagga the wind direction was predominantly northeasterly to easterly in accord with the pressure contours that lay along the coastal ranges (see Fig. 5 for a MSLP chart for this period). There were very strong diurnal modifications of wind speeds due to changes in boundary-layer characteristics, but the wind direction remained essentially constant. Figure 6 shows a time series of the winds at five heights above ground level and scattering intensity from the low frequency sodar during a typical day in this case study. The rapid acceleration of boundary-layer winds as convection ends near sunset is very clear (contrast the

Fig. 5 **Mean sea-level pressure chart for 2300 LT 8 January 2000 showing the continental scale heat low. Chart from the Australian Bureau of Meteorology MSLP archive, http://www.bom.gov.au/nmoc/MSL/index.shml.**

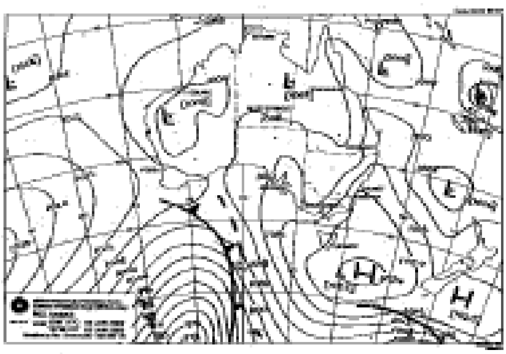
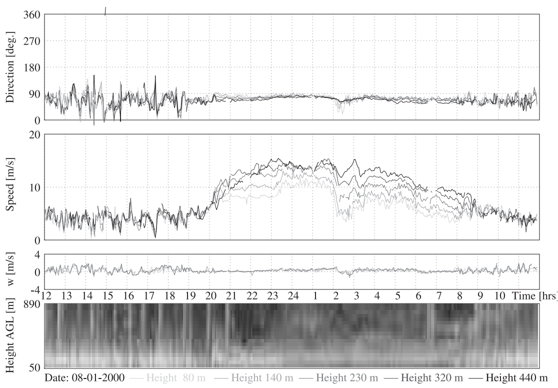


Fig. 6 **Plots of sodar data from Wagga Wagga, 1200 LT 8 January to 1200 LT 9 January 2000. The lowest panel is a time-height section of backscatter intensity from the sodar (light shades indicating high scattering intensity, dark shades indicating low scattering intensity). Remainder of the plot is (going up the page): time series of vertical wind speed at 80 m, 140 m and 230 m; horizontal wind speed and wind direction at 80 m, 140 m, 230 m, 320 m and 440 m AGL. Gaps in the time series indicate regions where data quality was poor and subsequently data were rejected.**



vertical winds before and after 1900 LT). The sodar and wind profiler profiles show that at night, a strong nocturnal jet develops as the winds within the boundary decouple from the surface. During the day the boundary layer is mixed by strong convection so that the average wind speed is quite low.

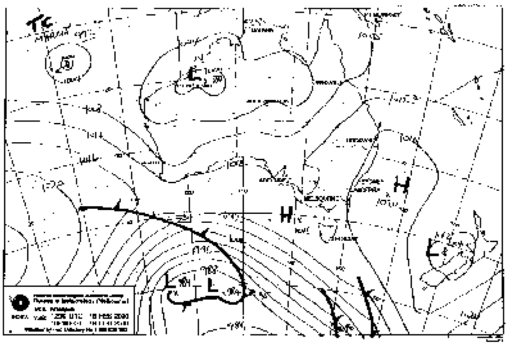
Why were no easterly intrusions observed during this apparent period of strongly favourable conditions? Our argument is that during this period the continental-scale thermal forcing was sufficiently strong and spatially uniform to completely dominate local or mesoscale processes. Thus, even though the predominant flow was thermally driven, there were no front-like intrusive flows. In summary, in the absence of spatial and temporal changes in the gradients in the wind field, there is no tendency for mesoscale surge development.

Case II: 16-18 February 2000 (mesoscale thermal forcing important)

On each of these three days, easterly intrusions were observed in Canberra in the late afternoon, and later at Wagga Wagga. There was also an intrusion to Canberra on 15 February. On the same day in Wagga Wagga the winds tended easterly all times so no surge-like intrusion was discernable. For the case study period the diurnal variation in the Ulladulla to Wagga Wagga pressure difference (Fig. 4) was very similar to the average summer time values, and thus was significantly weaker than the January case above. This smaller average pressure difference and amplitude of the diurnal cycle indicates that continental scale thermal forcing is weaker, and this interpretation is confirmed by inspection of the MSLP charts for the time, an example of which is given in Fig. 7. As a result, mesoscale thermal forcing due to the plateau effect and the land-sea contrast was important in this case.

The spatial variability of the forcing through this period is illustrated by the regional scale variation in the pressure gradients forcing the flow. Figure 8(a) shows the MSLP difference between Ulladulla and three other stations (Braidwood, Canberra and Wagga Wagga), normalised by the east-west component of the distance between those stations and Ulladulla. Because the along coast variation of MSLP was small, this is a good estimate of the east-west (range-normal) pressure gradient for this period. Because of the variation in the altitudes of these four stations (from 660 m to sea level), the method of reducing station level pressure to MSLP is critical to the interpretation and validity of these plots. Previous studies (Garratt 1984; Seaman 1997) have shown that the standard Bureau of Meteorology method of pressure reduction, which uses the mean monthly temperature for the fictitious column of air below the station, can produce erroneous pressure gradients in regions of elevated terrain when the mean temperature differs significantly from the long-term monthly average. The World Meteorological Organization (1968) recommends using the average of the temperature at the time of the

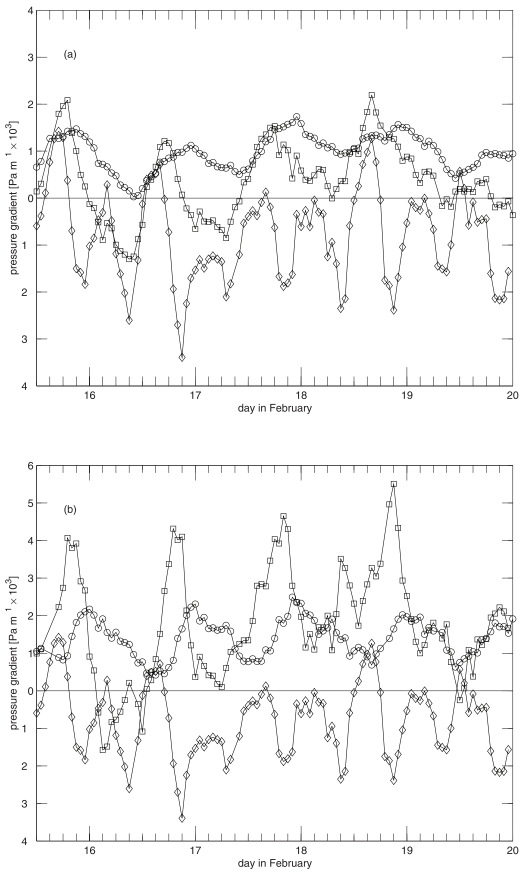
Fig. 7 Mean sea-level pressure chart for 2300 LT 16 February 2000 showing a relatively weak inland pressure gradient. Chart from the Australian Bureau of Meteorology MSLP archive, http://www.bom.gov.au/nmoc/MSL/index.shtml.



observations and twelve hours previous to the observations to reduce station level pressures to MSL. Seaman (1997) found that the WMO method generally performed well in eastern Australia, and Garratt (1984) also recommended the adoption of pressure reduction techniques that take actual column temperatures into account. This WMO approach has been taken for the MSLP reductions undertaken herein.

The characteristics of the pressure gradient on Fig. 8(a) change considerably as we move inland. The Ulladulla to Braidwood pressure gradient had a dominant semidiurnal variation. The pressure gradient was favourable to flow onto the plateau in the early afternoon on the four days in which intrusions were observed to reach Canberra (although the pressure gradient was only marginally favourable on the afternoon of 17 February). In contrast, the Ulladulla to Wagga Wagga pressure gradient variation was dominated by a diurnal component (due to the inland heat low) with a maximum gradient just before midnight, around the time of arrival of the intrusion on the three intrusion days. There was also a significant and increasing mean pressure gradient between Ulladulla and Wagga Wagga on the three days of the case study. The Ulladulla to Canberra pressure gradient was predominantly diurnal but had a small semidiurnal component. The maximum Ulladulla to Canberra gradient usually occurred two hours after the maximum Ulladulla to Braidwood gradient, in the early evening (between 1700 LT and 1900 LT on the first three days), but approximately an hour earlier and in-phase with the Braidwood peak on the last intrusion day.

Fig. 8 (a) Mean sea-level pressure gradient time series between Ulladulla and Braidwood (diamonds), Ulladulla and Canberra (squares), and Ulladulla and Wagga Wagga (circles). (b) Mean sea-level pressure gradient time series between Ulladulla and Braidwood (diamonds), Braidwood and Canberra (squares), and Canberra and Wagga Wagga (circles). For both frames, on the horizontal axis large tic marks labelled with day number indicate 0000 LT and small tics are spaced at three-hour intervals.



In Fig. 8(b) we look further at the spatial variation of the pressure gradient from the coast to the inland by comparing the Ulladulla to Braidwood pressure gradient (repeated from Fig. 8(a)) with the Braidwood to Canberra and Canberra to Wagga Wagga pressure gradients. The picture of the forcing for this case study that emerges from Fig. 8(a) is that the strongest gradients were between Braidwood and Canberra, especially in comparison with the weaker Ulladulla to

Braidwood gradients. These pressure gradients and initialisation of the easterly intrusions are due to the mesoscale differential heating mechanism, the plateau effect, discussed earlier. The rapid decrease of the pressure gradient between Canberra and Braidwood shown in Fig. 8(b) is consistent with the relatively intense but short duration of the intrusive flow in Canberra. The larger scale continental differential heating effect gives a weaker gradient between Canberra and Wagga Wagga, and Ulladulla and Wagga Wagga (Fig. 8(a)), than between Braidwood and Canberra, but this gradient is maintained through the night and this must be important in driving the intrusions inland to Wagga Wagga.

Figure 9 shows a time series from the Canberra sodar from the final day of this case study (the night of 19 February) illustrating a strong intrusive flow in Canberra only between 2000 and 2300 LT. For the three case study days there was an increase in the Canberra to Wagga Wagga gradient as the Braidwood to Canberra gradient reached its maximum value and rapidly decreased. The longer duration of the favourable gradient between Canberra and Wagga Wagga is responsible for the more sustained intrusive flow in Wagga Wagga (contrast the intrusive flow in Fig. 10 at Wagga Wagga with that in Fig. 9 at Canberra). At Wagga Wagga the inland flow following the intrusion front flow persisted until it was mixed out by the onset of convection in the morning.

Looking over the whole study region we found that pressure gradient time series for Ulladulla to West Wyalong, and Ulladulla to Young, were consistent with the Ulladulla to Wagga Wagga gradients plot (Fig. 8(a)). Pressure gradients between Ulladulla and the other two tableland stations, Goulburn and Cooma, were more variable, with quite strong semidiurnal signals. In both cases, however, the overall coast-to-station forcing was stronger than was apparent between Ulladulla and Braidwood. The distance from Cooma and Goulburn to the coast is intermediate between Canberra and Braidwood and the coast. This results in the mixed characteristics of the gradients calculated using the pressure at these two stations.

In this case study the forcing is spatially variable, resulting in the observed surge development; and by the time the intrusion reaches Wagga Wagga the increase in wind speed and change in wind direction occur very rapidly. Although we argue that mesoscale thermal forcing is important in generating the easterlies, the large scale thermal forcing is still a significant factor and must be the cause of the substantial increase in the mass transported in the easterly flow that occurs between Canberra and Wagga Wagga.

Fig. 9 Sodar time series showing the passage of the intrusion through Canberra on 18 February 2000. Description of plot is as for Fig. 6.

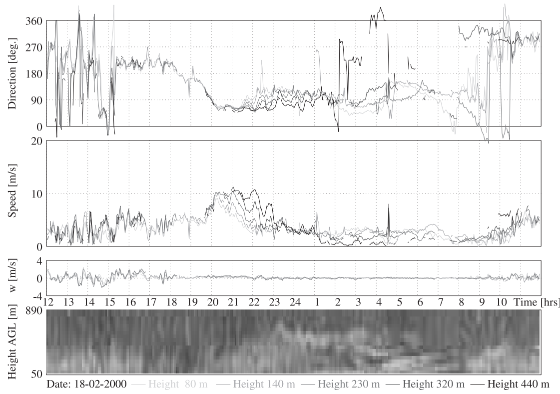
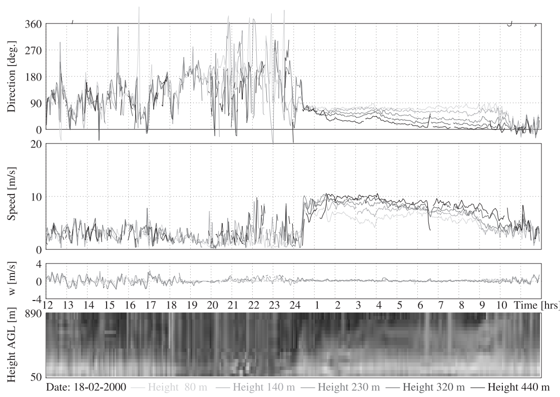


Fig. 10 Sodar time series showing the passage of the intrusion through Wagga Wagga early on 19 February 2000. Description of plot is as for Fig. 6.



The arrival time of the easterly changes at Braidwood (from the AWS data), Canberra and Wagga Wagga (sodar data) was used to estimate the average speed of the intrusion as it progressed inland from the coast, and the results are presented in Table 1. The low speed between the coast (where onset of the sea-breeze was between 1000 LT and 1100 LT) and Braidwood is consistent with Clarke's (1983, 1989) idea of an initial lack of connection between the sea-breeze and plateau effect circulations; the speeds in Table 1 are also consistent with this prior work.

Table 1. Estimated intrusion propagation speeds for February case study. Coast-normal distances are: 56 km coast—Braidwood; 63 km Braidwood—Canberra; and 181 km Canberra—Wagga Wagga. Uncertainties (figures in square brackets) are due to the uncertainties in measurements of the time for intrusion to move between successive locations.

Date	*Location*	*Speed [m s^{-1}]*
16 February	Braidwood	1.9 [0.2]
	Canberra	6.0 [1.1]
	Wagga Wagga AP	8.5 [0.4]
17 February	Braidwood	2.3 [0.2]
	Canberra	4.8 [0.7]
	Wagga Wagga AP	9.7 [0.5]
18 February	Braidwood	1.9 [0.2]
	Canberra	4.3 [0.5]
	Wagga Wagga AP	11.6 [0.6]

There was acceleration between Braidwood and Canberra, and a further substantial increase in speed between Canberra and Wagga Wagga. The magnitude of the intrusion propagation speeds and the evening acceleration are consistent with earlier observations of pure sea-breezes by Reible et.al. (1993). The acceleration of the intrusion in the evening can be ascribed to a combination of intensification of the front, and the reduction in turbulent stress as thermal convection decreases in the evening. The sodar backscatter image from Wagga Wagga (Fig. 10, lowest panel) shows that convection shuts down around 1830 LT, with a reduction in vertical velocity variation – i.e. decoupling – after 2400 LT, further evidenced by the abrupt change from quasi-vertical to quasi-horizontal structures in the backscatter image. Note that Fig. 9 (the equivalent picture for Canberra) does not show the same degree of stabilisation, even though one might expect a significantly larger cross-surge thermal contrast nearer the coast. Advection of cold air alone does not provide a transition to a stably stratified atmosphere.

Discussion and conclusions

It would be incorrect to label the summertime easterly intrusions observed in the study region as simple sea-breezes, as there is clearly a range of forcing mechanisms other than the land-sea temperature difference which are important in their development and propagation. The other forcing mechanisms relevant to the easterlies are differential heating at both meso- and continental scales, and post-frontal ridging. We observed significant changes in the propagation speed of the front and the characteristics of the following flow as the intrusions propagated between our two stations. As the boundary layer through which the intrusions propagate changes from unstable in the daytime to stable at night, the intrusive flow decouples from the surface and develops the characteristics of a low-level nocturnal jet. As a result there is little surface cooling associated with the intrusion by the time it has propagated as far inland as Wagga Wagga.

In future work, we will compare these observations with the results of a mesoscale model (TAPM, The Air Pollution Model; Hurley 2002), attempting to simulate the intrusive flows over the full experimental period. We also plan to explore two-dimensional simulations (using RAMS, the Regional Atmospheric Modelling System; Pielke et al. 1992), to more fully investigate both the initial development and subsequent evolution of the front-like characteristics of the easterly surge.

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