The wintertime nocturnal northeasterly wind of Adelaide, South Australia: an example of topographic blocking in a stably-stratified air mass

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Upstream air mass blocking is presented as the generating mechanism for the nocturnal northeasterly wind regularly experienced over the Adelaide Plain during winter. Theory and observations are presented which challenge the traditionally held belief that the wind is of katabatic origin.

Introduction

Nocturnal surface airflow over the Adelaide Plain during winter (June, July and August) is predominantly from the northeast. These winds have been associated with the rapid onset of low cloud drizzle and fog. They also affect nocturnal minimum temperatures, the movement of atmospheric pollutants and can be associated with low-level vertical wind shear hazardous to aviation traffic.

Local meteorologists have for many years been aware of the correlation between the northeasterly wind and the development of low stratus cloud and fog over the Adelaide Plain. Blake (1962) recognised that the northeasterly wind transported airborne pollutants across the Adelaide Plain under conditions which were also favourable for fog formation. A conceptual model of the developmental mechanism for low stratus was given by Broadbridge (1978) who described the northeasterly surface wind as katabatic flow down the western slopes of the Mount Lofty Ranges. He proposed that if a synoptic westerly airstream was sufficiently moist and the katabatic sufficiently deep, then the vertical displacement of moist air due to katabatic undercutting would result in the formation of cloud with a base close to the separation point between katabatic flow and the synoptic flow. He likened this conceptual model to a pseudo warm front.

This paper presents observational and theoretical evidence which challenges the previously held belief that the northeasterly flow is of a katabatic nature. The high frequency of nocturnal northeasterly surface winds is considered to be due to upstream air mass blocking by the Mount Lofty Ranges. A three-dimensional conceptual
model of blocked flow over the Adelaide region is presented.

Using an empirically-derived critical value for a modified Froude number it is shown that it is possible to ascertain whether air mass blocking is likely to occur, and that it is possible to compute the height of the transition layer through which blocked flow becomes unblocked (the separation level).

Adelaide, South Australia, lies just west of the Mount Lofty Ranges which extend some 60 kilometres to the south and 600 kilometres to the north (Fig. 1). The highest point of the ranges near Adelaide is Mount Lofty which rises to 711 metres.

The Adelaide Plain is bounded by Gulf St Vincent to the west and the Mount Lofty Ranges to the east. The coastline is oriented north/south while the ranges near Adelaide lie north-northeast/south-southwest. A spur of lower hills runs east-northeast/west-southwest to the gulf, about 10 kilometres south of Adelaide Airport, in the vicinity of Marino (Fig. 2).

![fig. 2 recording stations and topography of the Adelaide region; contour heights in metres.](image)

**Theoretical katabatic winds—Adelaide region**

Katabatic flows develop over sloping terrain on clear nights, usually in conjunction with a weak surface pressure gradient. Terrestrial radiation from the earth’s surface results in cooling of air close to the ground, relative to air at the same level that is not in contact with the ground, and gravity induces this denser air to flow down the slope. To establish steady-state flow the dynamics which initiate the flow must be present along the entire slope.

Spectacular katabatic winds occur over glacier plateaus where cooling near the ice surface is extreme. Valley systems generate complex katabatic flows due to the interaction of valley wall and floor slopes.

Nappo and Rao (1987) considered pure katabatic flow down a uniform open slope and developed a two-dimensional numerical model. Their results indicate that over a smooth slope of similar incline as the Adelaide Plain (0.3° from Adelaide Airport to the Mount Lofty foothills) within an ambient isothermal or neutrally stratified layer, katabatic flow would reach steady state at a speed of less than 1 m/s and a depth of less than 10 m. Their results also suggest that katabatic winds down the western escarpment of the Mount Lofty Ranges would be even weaker and shallower i.e. less than 0.5 m/s and only about 5 m deep.

Manins and Sawford (1979), using a one-dimensional model of katabatic flow, suggest that entrainment of ambient air is the dominating retardation mechanism of the flow and that surface stress is relatively unimportant. They indicate that over steep (~10°) slopes katabatic flow would be weak (1 m/s) and shallow (~10 m), and that significant katabatic flow over areas such as the Adelaide Plain is unlikely due to shallow inclination and limited fetch (the distance from foothills to coast is no more than 8 km). On intermediate slopes (~2°) which exist over small areas of the Plain the Manins and Sawford model predicts katabatic flow of the order of 1–2 m/s.

**Observed anomalies**

Observations of wintertime nocturnal winds over the Adelaide Plain have revealed the following anomalies if the flow is considered to be katabatic.

**Direction**

The orientation of the Mount Lofty Ranges and the slope of the Adelaide Plain suggest a katabatic wind direction from the east or southeast. However, the most frequently observed nocturnal wintertime surface flow (see Fig. 3) is from the northeast.
Speed
At Adelaide Airport the observed mean speed of the northeasterly is 1 to 3 m/s (Blake 1962). This has been observed to strengthen to 4 m/s with gusts to 6 m/s (Broadbridge 1978). These observed speeds are three to four times stronger than the theoretical katabatic flow.

Synoptic situation
The northeasterly wind often does not develop during ‘ideal’ katabatic conditions, that is, with light gradient flow and cloudless nights. Instead, northeasterly flow is commonly experienced with overcast conditions and often in conjunction with drizzle and low cloud. Similar flow has been observed to develop during daylight hours in rain situations.

Seasonal variation
The northeasterly wind is most frequently observed during winter months (Fig. 3) and rarely during summer (Fig. 4). Theory suggests that katabatic winds would occur more frequently in summer when the synoptic easterly wind might assist an easterly katabatic. The frequent clear nights would also favour strong surface radiational cooling.

Central Standard Time (CST) and the mean direction and speed for each sector computed. Surface winds corresponding to each gradient sector and time were averaged. It was found (Fig. 5) that:
(a) when the gradient is from the west-southwest, west-northwest or north-northwest sector;
(i) the 1500 CST surface wind direction is within a few degrees of the gradient direction.
(ii) significant veering (~55°) of the surface wind occurs between 1500 and 2100 CST after which directional changes are minimal. By 0900 CST the wind shows a tendency to back.
(b) when the gradient wind is from the south-southwest sector significant backing of the surface wind occurs overnight;
(c) when the gradient wind has an easterly component;
(i) the surface wind at 1500 CST is not closely related to the gradient except in the north-northeast sector.
(ii) overnight wind direction shifts are highly variable.

It is apparent that there are significant variations in the diurnal surface wind behaviour for different gradient wind directions at Adelaide Airport. Most notable is the consistent wind behaviour for ‘on-range’ gradient flow (north-northwest, west-northwest, west-southwest). Here the tendency for a rapid veering toward the northeast is evident between 1500 and 2100 CST. Other sectors do not exhibit this strong tendency to veer from the gradient direction. Holton (personal communication) has constructed hodographs for winter which produce similar results. His summer charts show that there is no significant tendency for nocturnal winds to shift to the northeast. Theory would suggest that katabatic winds should not depend on the direction of the gradient wind.

Further anomalies come to light if we look in

Fig. 3 Winter wind frequency, 0300 CST Adelaide Airport (1954/1984).

Fig. 4 Summer wind frequency, 0300 CST Adelaide Airport (1954/1984).

Depth
Theoretical katabatic flow over a slope of small inclination has been shown to be shallow (Nappo and Rao 1987), but observations of smoke plumes over the Adelaide Plains indicate that the transition layer between surface northeasterly flow and the ambient synoptic flow is often as high as 300–400 metres.

Relationship of gradient wind to surface wind
Adelaide Airport gradient level (600 m) winds for the winter months (June, July and August) of 1986 and 1987 were subdivided into eight directional sectors for the times 1500, 2100, 0300 and 0900
Fig. 5  Hodographs of the diurnal variation of the surface wind for eight 600 m wind sectors (SSW, WSW, WNW, NNW, NNE, ENE, ESE, SSE) based on data from 1986 and 1987 winters. Large symbols represent the mean 600 m wind for each sector. Small symbols show the mean surface wind at six-hour intervals corresponding to each sector.

detail at the observed surface winds under light gradient wind regimes. All situations with gradient flow less than 5 m/s for the 1986 and 1987 winters were considered. These were subdivided into easterly and westerly categories. The comparison between mean gradient winds and the mean surface winds at 2100 and 0300 CST for each category is shown in Table 1. For gradients from the west, the surface winds are 1.5 (2100 CST) to 2.5 (0300 CST) times stronger than those for gradients from the east. Simple katabatic theory would suggest that a katabatic wind should not exhibit greater strength when the ambient wind is opposing it.

Table 1. A comparison of mean nocturnal surface winds in light gradient flows (1986, 1987 winters). Wind speeds in m/s, direction in degrees true.

<table>
<thead>
<tr>
<th>Gradient direction</th>
<th>Mean surface wind</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2100 CST</td>
</tr>
<tr>
<td>East</td>
<td>068/0.8</td>
</tr>
<tr>
<td>West</td>
<td>032/1.1</td>
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These results do not categorically rule out the existence of a katabatic influence at Adelaide Airport, nor rule out the possibility of localised pock-ets of katabatic flow over limited areas of the Adelaide Plain. However, they do strongly suggest that general katabatic winds would be very light and should blow from the east or southeast. This is supported by the theoretical katabatic flow derived from the models of Nappo and Rao (1987) and Manins and Sawford (1979).

Upstream air mass blocking

Upstream air mass blocking in stably stratified flows has been well documented. Kao (1965) noted the occurrence of a stagnant zone in stably stratified fluid windward of an obstacle separated from the remainder of the flow by a line of velocity discontinuity. He found an inverse relationship between the height of the stagnant or blocked layer and a modified Froude number. Kitabayashi (1977) found regions of stagnant flow upstream of a topographic ridge and defined the stagnant flow layer as that where there was no airflow or where the flow was actually away from the obstacle; that is opposite to the ambient flow. Pierrehumbert and Wyman (1985) found upstream blocking occurring windward of the Alps during the Alpine Experiment (ALPEX). They looked at the effect on a relatively large scale and found the controlling parameters to be the Rossby number and the parameter Nh/u, where N is the Brunt Vaisala frequency, h is the barrier height and u is the speed of the oncoming flow. Baines (1979, 1987) examined the effect on stably stratified flow at large Reynolds numbers and found that totally blocked fluid was observed upstream of a two-dimensional barrier with Nh/u > 2. For the same barrier with a gap and Nh/u > 2, all the incident fluid below a certain height flowed around the barrier and through the gap. Partial blocking was observed to occur when Nh/u < 0.5.

Mesoscale pressure and wind systems, anomalous to the synoptic pressure field, have been observed in many localities during blocking events. Bonner and Paege (1970) observed that variations in surface winds over mountainous terrain in the south central United States were closely linked to the diurnal temperature cycle. Parrish (1982) found near stagnant air windward of mountains in strong synoptic pressure gradients. Pierrehumbert and Wyman (1985) found pronounced (~ 90°) veering of the wind in a layer little more than 100 m deep upstream of the Alps. Schwertfeger (1975) observed low-level winds blowing parallel to terrain contours in Alaska and along the Antarctic Peninsula. He found that the anomalous low-level winds were a mesoscale phenomenon which occurred in a stably stratified air mass impinging on mountains.

The experimental work of Baines (1979) has shown how blocked fluid will migrate towards a gap in a barrier. The topography of the Adelaide
region simulates a barrier with a gap. The Mount Lofty Ranges constitute the barrier (of great northward extent), with the area of sea to the west, where the ranges run into Gulf St Vincent near Marino, representing the 'gap'. Blocked air over the plain will migrate southwestward towards this gap since there is no 'escape' to the north.

An additional mechanism likely to influence the direction of the surface flow is the external pressure gradient acting on the blocked fluid. The geostrophic pressure force associated with gradient winds from the north-northwest through to the west-southwest (on-range flow) has in all cases a southward component. This pressure force acts on the blocked fluid in the Adelaide region, forcing it to the south.

It is thus proposed that the northeasterly flow is a combination of:
(a) the migration of blocked fluid towards a gap in the barrier, and
(b) the response of blocked fluid to the external pressure force.

**Observational support**

Long-term wind direction frequencies for winter indicate that surface winds over the Adelaide

Plain in the afternoon closely parallel the vector mean gradient wind (Fig. 6(a)). However, during the night and early morning the surface winds flow virtually parallel to the topographic contours. Figure 6(b) shows this type of flow up to an elevation of 225 m at Black Hill. However, at an elevation of 305 m (Belair) the surface wind is almost parallel to the gradient wind. A marked directional shear exists between 225 m and 305 m during the period when stable stratification is frequent.

Wind frequency distributions for Adelaide (Fig. 7(a)) and Parafield (Fig. 7(b)) Airports show the mean surface flow at 0300 CST. The most frequently observed wind is from the north-northeast or northeast, virtually parallel to the ranges, while the vector mean gradient wind is from the west-northwest.

Mean surface winds were derived from continuous wind records from Adelaide and Edinburgh Airports (1986/87), Kent Town (1986/87), Northfield (1987), Gawler (1987), Outer Harbour (1986) and Port Stanvac (1986). Surface winds for 0300, 0900, 1500 and 2100 CST corresponding to gradient winds from the north-northwest, west-northwest and west-southwest directional sectors are shown in Figs 8, 9 and 10. These surface flow

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**Fig. 6(a) Most frequent direction of gradient and surface winds at 1500 CST, winter 1986/1987.**

**Fig. 6(b) Most frequent direction of gradient and surface winds at 0900 CST, winter 1986/1987.**
patterns indicate that, whilst the gradient wind speed and direction show little diurnal variation, the surface winds:
(a) flow almost parallel to the gradient flow during the day;
(b) nocturnally veer over the plain to a direction near parallel to the topographical contours but continue to parallel the gradient flow nearer the top of the barrier; and
(c) are 2–3 m/s stronger in the south. Port Stanvac, unlike other locations, shows little diurnal variation in speed and actually has greater speed than Mount Lofty at night.

The increase in surface wind speed in the south may be attributed to the confluence of the ambient flow over the gulf and the blocked air moving southwestward towards Marino.

Further observational support for air mass blocking and along contour flow in the Adelaide region comes from a pilot who operates hot air balloons over the Barossa Valley, some 25 km east of Gawler. For early morning flights he often uses the high-level ambient westerly winds to position the balloon over the valley, before descending below ridge-top level into a wind which flows parallel to the valley contours.

Determination of a minimum critical \( Nh/u \) value for blocking

Surface flow at Adelaide Airport was deemed to be totally blocked if the 600 m wind was from 225° to 360° (on-range flow) and the surface wind: (a) was from 030° to 210°, i.e. was parallel to or had a component away from the ranges; or (b) was calm.

Surface flow was deemed to be partially blocked if (a) did not apply but veering of greater than 45° from 600 m flow occurred. Data were insufficient to accurately determine separate values for \( Nh/u \) for totally blocked and partially blocked situations. Our derived \( Nh/u \) value thus applies to both blocked or partially blocked flow.

In calculating \( Nh/u \), the actual value of \( u \) was used rather than the on-range component for two reasons:
(a) the orientation of the Mt Lofty Ranges varies from about 340° in the north to 060° near Marino, making a representative orientation for blocking at Adelaide Airport difficult to determine; and
(b) using the on-range component of \( u \) will only increase the computed value of \( Nh/u \). We are
Fig. 8 Mean diurnal surface wind variation for the NNW gradient wind sector 1986/1987.
Fig. 9  Mean diurnal surface wind variation for the WNW gradient wind sector 1986/1987.
Fig. 10  Mean diurnal surface wind variation for the WSW gradient wind sector 1986/1987.
interested in the minimum critical value for \( N_h/u \). To calculate \( N_h/u \) for Adelaide Airport

\[
N_2 = g/\theta \frac{d \theta}{dz} \approx g/\theta \frac{\Delta \theta}{\Delta z}
\]

where \( g = 9.8 \text{ m/s} \), \( \theta = 285 \text{K} \) (the mean potential temperature of lowest 600 m for Adelaide in winter), \( \Delta \theta = \theta \) difference between surface and the top of the stable layer, \( \Delta z = \text{the height of the stable layer} \), \( h = 600 \text{ m} \) (the effective height of the barrier), and \( u = 600 \text{ m wind} \).

Using 1986/87 data it was found that partial or total blocking would occur when \( N_h/u > 0.85 \). Given the errors inherent in the determination of \( \Delta \theta (\pm 0.25^\circ) \), \( \Delta z (\pm 25 \text{ m}) \) and \( u (\pm 1 \text{ m/s}) \) the overall error in the determination of \( N_h/u \) was about 20 per cent. More detailed observational data are required to accurately determine a value for \( N_h/u \) when the flow is totally blocked.

Using mean data from Adelaide Airport for July, it was found that at 0900 \( N_h/u \) had a value of 1.0. At 1500 \( N_h/u \) had a value of 0.0. These results show how \( N_h/u \) varies diurnally, with the respective values indicating that partial or total blocking is likely during the early morning, but very unlikely during the afternoon.

**Dividing streamline**

The dividing streamline, or separation height, between the blocked and unblocked flow is defined as the level where (with blocking established) the greatest vertical wind shear occurs (up to a height of 600 m).

From Sheppard (1956):

\[
h_d/h = 1 - Ku/N_h
\]

where \( h_d \) = the height of the dividing streamline, \( K = \text{constant} \), and \( h = \text{height of the barrier} \). Taking \( h = 600 \text{ m} \) we find \( h_d = 600(1 - 0.85 u/N_h) \).

For 1987 winter the average calculated value for \( h_d \) was 270 m. For every blocked event the calculated value was compared with the observed separation height (from Adelaide Airport balloon flight). A rms difference of 140 m was found which is well within the vertical resolution of the radar observed low-level winds.

**Conceptual model**

A conceptual model of the three-dimensional flow structure over the Adelaide region with a blocking regime established is shown in Fig. 11.

**Some consequences of upstream blocking in the Adelaide region**

When low-level air over the Adelaide Plain is blocked, the relatively warm air from the Gulf St Vincent will ride up and over the blocked layer. If this air is sufficiently moist, and the lifting sufficiently great, then low cloud and/or precipitation may develop over the plain. The injection of additional moisture into the blocked layer can increase the dew-point temperatures and result in a lowering of the cloud base or fog formation, which can be critical for aviation. Precipitation associated with synoptic fronts or troughs can be enhanced by this warm frontal-type lifting action. Atmospheric pollutants which become trapped in the blocked air mass can become concentrated over the western suburbs of Adelaide when advected by the northeasterly wind. Significant low-level vertical wind shears and a low-level jet are occasionally generated near the dividing streamline. The low-level wind profile of such an event, on 21 August 1987, is shown in Fig. 12. Such vertical wind shear required an aviation wind shear warning to be issued for Adelaide Airport. Nocturnal temperatures over the Adelaide Plain can be higher than expected in cloudless conditions with light gradient winds due to turbulent mixing associated with the northeasterly wind.
Conclusion

Upstream air mass blocking of stably stratified flow by the Mt Lofty Ranges is proposed as the main generating mechanism of the northeasterly surface flow across the Adelaide Plain on winter nights. A southward-acting pressure force, combined with the tendency for blocked flow to migrate toward a gap, are believed to contribute to the observed mountain-parallel wind.

Blocking can lead to significant modification of local weather conditions as the blocked wind regime simulates a mesoscale quasi-stationary warm front. Although there is a pronounced preference for blocking to occur during the nocturnal hours of winter, it can occur at other times when suitable conditions arise. It is intended that this work assist in a greater understanding of the structure and developmental mechanism of the wintertime nocturnal flow over the Adelaide Plain, and with this an increase in forecast skill of low cloud and fog, low-level wind shear, minimum temperatures and movement, and dispersion of airborne pollutants.

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