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The sea-breeze — forecasting aspects

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Cases where the land-sea temperature difference gives rise to modification of the surface wind as a sea-breeze effect at the Royal Australian Navy Air Station, Nowra, New South Wales, have been studied for the period 1958 to 1977. A relationship is found between the strength of the sea-breeze component and the land-sea temperature difference, and estimates are found for the penetration inland of this effect. These relationships can be used to forecast variation of surface winds due to the sea-breeze at near-coastal stations.

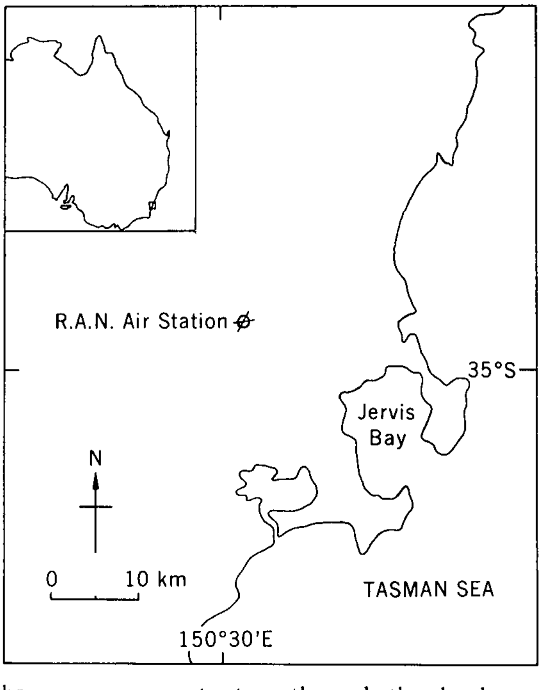
Introduction

The occurrence of temperature differentials across the surface of the earth leads directly to pressure variations that give rise to air movement. At the mesoscale level, this effect may range from local sea-breezes and mountain winds to the formation of thermal lows over land masses in summer. These phenomena are superimposed on the synoptic and global scale circulations, and the prediction of their contributions to the resultant air flow is an important aspect of forecasting at an airfield, especially as it affects planning of which runway to use and on very hot days may well lead to critical low-lift conditions if the resultant wind is very light.

The effects of the sea-breeze have been studied at the Royal Australian Navy (RAN) Air Station, Nowra, New South Wales, and the results compared with findings at other locations. The RAN Air Station is 15 km from the nearest coastline, which has an overall orientation of approximately 020°-200° (see Fig. 1). Runway elevation is 108 metres, and the terrain from the coast slopes gradually and is lightly timbered.

This analysis includes not only those cases where a net onshore wind results, but also those where, for example, an offshore wind has its strength reduced by the opposing thermal driving mechanism.

Fig. 1 Location map, RAN Air Station, Nowra.



Effect of sea-breeze on surface wind

The actual wind recorded at the surface will depend on both the gradient wind, towards which it will normally tend as thermal mixing occurs in the lower layers after sunrise, and the sea-breeze component (if any), these two components being added vectorially.

The magnitude of the sea-breeze component depends on the land-sea temperature difference. Defant (1951) found a linear relationship between sea-breeze component strength and temperature difference. However, the present study suggests that a linear relationship between the square of the sea-breeze component strength and the land-sea temperature difference might be more appropriate.

The sea temperature is approximately constant during a given 24-hour period, whereas the land temperature is subject to significant diurnal variation. The amount of this variation depends on the synoptic situation with regards to the air mass affecting the area concerned. For example, at the RAN Air Station, Nowra, the large summer temperature differences are characterised by northwesterly winds, while the smaller summer differences are usually associated with prevailing easterly (onshore) gradient winds.

The net result is that the sea-breeze has a slight enhancement on prevailing easterlies, and a marked effect, in both strength and direction, on surface winds in a prevailing westerly situation.

Observations of sea-breeze components

As a result of the considerations outlined in the previous section, any observations of sea-breeze component are most easily made in a westerly airflow in summer, irrespective of the strength of the gradient, or where the sea-breeze is much stronger than the gradient. Care was taken in the present analysis to ensure that the modification of the surface wind was indeed caused by the sea-breeze effect and not by a change in the synoptic situation. Surface winds were measured by an anemometer at a height of 10 metres above ground.

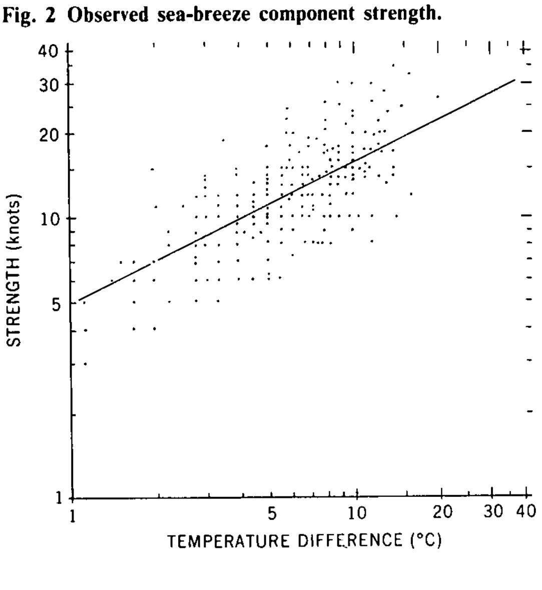
Data have been extracted from records for the summer months from 1958/59 to 1976/77 where conditions indicated a true sea-breeze effect, and the results of this analysis are depicted in Fig. 2. These results are plotted in logarithmic scales for both T and the sea-breeze component strength. As a first-order line-of-best-fit for these data, the solid line on Fig. 2 represents the relationship

$$v = 5.(\Delta T)^{1/2} \text{ knots} \qquad \ldots 1$$

for ΔT in degrees Celsius, ΔT being the difference between the air temperature (T_{air}) at Nowra and the sea-surface temperature (T_s) of adjacent near-coastal ocean waters. The latter was based on climatological data, supplemented with actual ship observations as available.

The direction of the sea-breeze component varied mainly in the range 080°-130° for all strengths. There was an indication that lighter components tended to be from between 080° and 110°, with stronger components being more predominantly within the sector 110° to 130°, but the accuracy of

Fig. 2 Observed sea-breeze component strength.



data and sample size were insufficient to lead to a definite conclusion in this regard. However, if this variation is real, it would imply that the water of Jervis Bay has an influence on the sea-breeze effect in the surrounding region, with a result similar to the two-component sea-breeze noted by Physick and Byron-Scott (1977) for the shores of Gulf St Vincent. Jervis Bay is a near-circular body of water, approximately 13 km in diameter, and whose centre is on an approximate bearing of 130° from the Air Station (see Fig. 1). The deflection of the resultant sea-breeze from the line of maximum temperature gradient due to the effect of Coriolis' force may also be significant in leading to variations of the characteristic sea-breeze component directions.

Penetration of sea-breeze

The daily heating rate is approximately sinusoidal and it follows that the air temperature exhibits the same functional variation. However, the quantity that is of interest for the purpose of this analysis is the difference between the air temperature and the local sea temperature, in particular, when the air temperature is the higher. In summer, the sea-surface temperature is typically much less than the daily mean maximum air temperature and somewhat above the overnight minimum air temperature (except when nocturnal radiation is inhibited by the presence of low cloud).

Hence, the quantity ΔT from the time when $\Delta T = 0$ through to the time of onset of the sea-breeze will have an approximately linear variation with time, to the first order, for places nearest to the land-sea boundary, provided that the onset of the sea-breeze occurs significantly before the time of maximum insolation. Such a linear relationship will be used to find an estimate of the rate of penetration of the sea-breeze component, and, conversely, of the time of onset at a given station.

Therefore, let

$$\Delta T = kt \qquad \ldots 2$$

where k is the (forecast) hourly rate of increase of air temperature prior to the onset of the effect of the sea-breeze, and $t = 0$ when $\Delta T = 0$.

Equation 1 then becomes, for the sea-breeze strength,

$$v(t) = 5(kt)^{1/2} \text{ knots} \qquad \ldots 3$$

The relationship between the propagation speed of a mesofront and the strength of the flow astern of such a front has been investigated by Clarke (1961), Goff (1976) and Simpson and Britter (1980). The latter performed laboratory experiments with aqueous solutions of fractionally different density to simulate air masses of differing temperature, but their results were consistent with the thunderstorm outflow data of Goff and the sea-breeze data of Clarke.

For near-calm conditions ahead of the front, Clarke found that

$$V_f = {}^2/_3\, V \qquad (V_a = 0) \qquad \ldots 4$$

while in the more general case, Goff's study of 20 thunderstorm outflows gave a relationship

$$V_f = 0.7\, V + 0.3\, V_a \qquad \ldots 5$$

where V_f is the speed of the mesofront, V_a is the ambient wind speed ahead of the mesofront, and V is the wind speed astern of the mesofront.

On the other hand, Pearson (1973) demonstrated theoretically that the speed of the front was not directly correlated to the maximum observed velocity in the sea-breeze, but was related only to the total heat input of the air. Specifically, he found a linear relationship between the square of the frontal speed and the total heat input.

If it is assumed that the effect of the sea-breeze component propagates inland at a proportion, $\alpha(=V_f/V)$, of the speed of the sea-breeze component, then it will cover a distance given by

$$d(t) = \alpha \int_0^t v(t)\, dt$$

$$= 3.3\alpha k^{1/2} t^{3/2} \text{ nautical miles}$$

$$= 6.2\alpha k^{1/2} t^{3/2} \text{ kilometres} \qquad \ldots 6$$

This is represented in Fig. 3 for different values of $\alpha^2 k$.

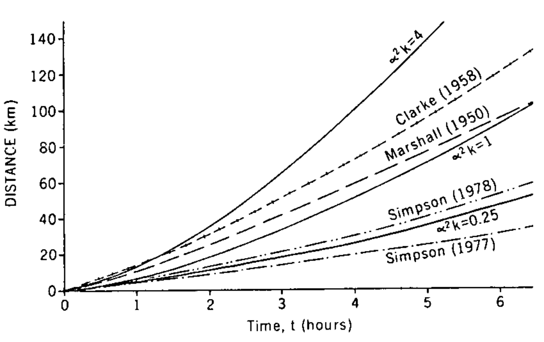
Sea-breeze penetration has been investigated at a number of locations, covering a range of rates of heating (Marshall 1950; Clarke 1958; Simpson et al. 1977). Curves representing these rates of movement inland are included in Fig. 3 and are consistent with the curves representing Eqn 6.

The time of onset of the effect of the sea-breeze component at a particular location on each occasion can be forecast after an estimation for the value of $\alpha^2 k$ is made. The corresponding penetration curve can be interpolated on Fig. 3 for this estimated value also.

For example, at Nowra (d=15 km), Eqn 6 gives

$$t^3 = 5.9/\alpha^2 k \qquad \ldots 7$$

Fig. 3 Inland penetration of sea-breeze front.



Other observations

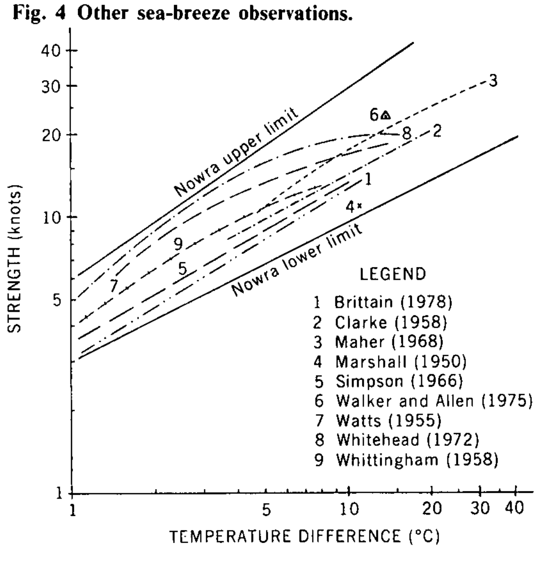
Observations of sea-breeze have been made over a long period and over a wide range of locations. Likewise, results of such observations have been presented in a variety of formats but most lend themselves to be processed so that comparison can be made against Fig. 2. In some cases, climatological data have been added to published results when it was appropriate to do so. Figure 4 shows the upper and lower limits of sea-breeze component strength from Nowra data, together with plots derived from other sources.

Marshall (1950) describes a sea-breeze that penetrated 150 km up the Thames Valley. From the time of passage across London, it can be concluded that the quoted temperature of the air ahead of the front was close to the maximum for that day. The climatological sea-surface temperature then completes the information necessary to allow a single-point plot on Fig. 4. Walker and Allen (1975) tabulate a set of observations that result in a closely-grouped plot on Fig. 4.

Other studies lead to tables of values of ΔT necessary to overcome an opposing gradient wind, or scatter diagrams of 'sea-breeze-days' and 'non-sea-breeze-days' over a range of values of gradient winds and temperatures. These include Watts (1955), Clarke (1958), Simpson (1966), Maher (1968), Whitehead (1972) and Brittain (1978), and the results are plotted as curves on Fig. 4.

Whittingham (1958) tabulates mean hourly winds for Brisbane for each month of the year. At the latitude of Brisbane, the number of occurrences per month of wind changes due to frontal passages would be much less than of sea-breezes. Hence, the mean maximum onshore wind is very nearly the combined effect of the mean gradient wind plus the mean maximum sea-breeze strength. Using climatological data of mean gradient winds, the

Fig. 4 Other sea-breeze observations.



mean maximum sea-breeze component can be calculated and plotted on Fig. 4 against ΔT values estimated from climatological data for sea-surface temperatures and mean daily maximum air temperatures.

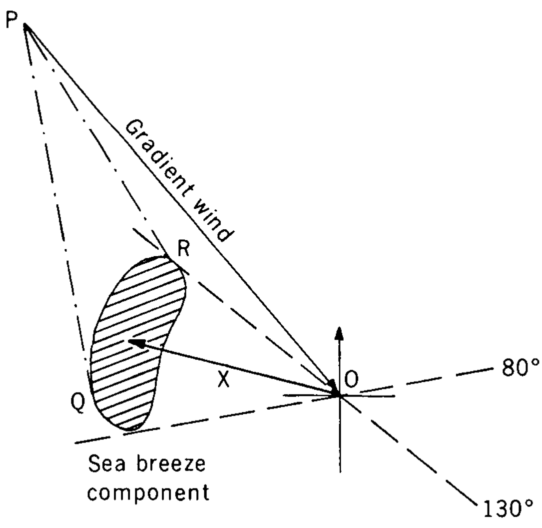
Forecasting the effect and timing of sea-breeze

To forecast the effect of sea-breeze during the day, the forecaster needs to predict the maximum temperature that will be reached. Of course, the maximum temperature will itself be affected by the timing of the onset of the sea-breeze component.

For timing considerations, the forecaster needs additionally to estimate the time at which the air temperature over the land will first exceed the sea-surface temperature and the hourly rate of increase of the air temperature (k) over the land thereafter, and calculate an expected value of a using Eqn 4 or 5.

From the estimated maximum temperature, and the known sea-surface temperature, Fig. 4 gives upper and lower limits for the maximum strength of the sea-breeze component. Together with the possible variation in characteristic sea-breeze component direction, this can be represented by the shaded sector in Fig. 5. If the gradient wind is added vectorially to the diagram (represented by PO), then the resultant wind with maximum sea-breeze component could vary in direction from PQ to PR and similarly in strength.

Fig. 5 Determination of resultant wind (see text).



The transition should theoretically start at a time such that t is given by Fig. 3 for the appropriate value of a^2k and the distance of the observing station from the land-sea boundary. From this time to the time of maximum sea-breeze component, the description of the transitional variation may be based on considerations of the changes in vector PX as X moves from O to the centre of the shaded area (Fig. 5). This will determine whether the resultant wind backs or veers and how the resultant wind strength varies with time. Typical situations are depicted in Figs 6(a) and (b).

In actual practice this transitional sequence will be modified by the diurnal variation of the geostrophic component of the wind. Overnight the surface wind drops well below the gradient strength and often to calm conditions, then steadily builds up to its final value as thermal mixing of the lowest layers takes place in the hour or two immediately after sunrise. Therefore, the resultant wind during the forenoon will depend on when the condition $T_s = T_{air}$ occurs in relation to sunrise, and the relative strengths of the gradient wind and sea-breeze components at any given time.

As an example, Fig. 7 represents a warm day with a light northwesterly gradient. The sea-breeze component was evident early as it first led to a decrease in the resultant northwesterly wind, then to a veering to the east with subsequent increase in the net onshore flow.

Fig. 6(a) Transition variation when gradient wind stronger than maximum sea-breeze component. Resultant strength decreases steadily; wind veers slightly from original NW (or would back slightly from an original SW direction).

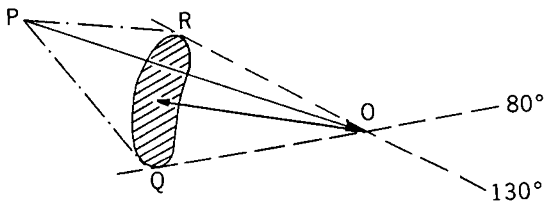
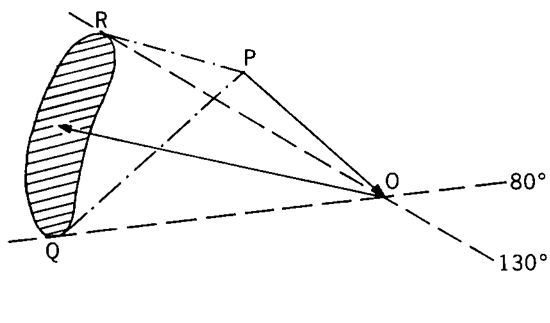


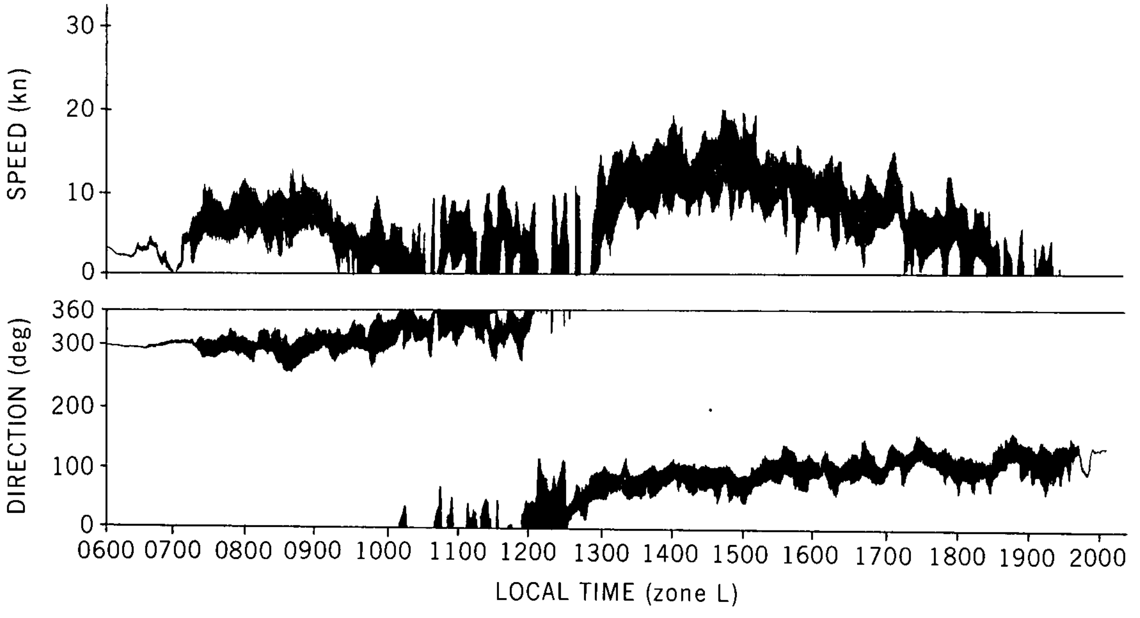
Fig. 6(b) Transition variation when gradient wind weaker than maxium sea-breeze component. From NW, resultant veers to E to NE (from SW, it backs to E to SE). The strength decreases through a minimum and then increases from the onshore direction.



Conclusion

The relationship between sea-breeze component strength and the land-sea temperature difference has been established from data obtained at the RAN Air Station, Nowra, and it has been shown that it is consistent with results of sea-breeze studies in many other locations. This relationship has been used to devise a systematic approach to forecasting the variations in surface wind resulting from the strengthening of the sea-breeze component, and the timing of these variations. Based on such forecasts, aviation operations personnel at airfields can anticipate changes to flying conditions including changes in runways to be used.

Fig. 7 Anemograph trace for 14 December 1976.



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