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METEOROLOGICAL OFFICE

FORECASTING TECHNIQUES MEMORANDUM

Nº 20

# FORECASTING THE INLAND PENETRATION OF A SEA BREEZE OVER LINCOLNSHIRE

by

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## Foreword

The present paper discusses the inland penetration of the sea breeze over Lincolnshire in terms of a model based on the particle dynamics approach. The model relies on some fairly drastic assumptions: in particular it is assumed that

a. the sea-breeze motions have no effect on the pressure field, and indeed that the pressure field remains steady, and

b. the effect of friction on the development of the sea breeze can be neglected.

However, in spite of the model's simplicity and neglect of some possibly important effects, it appears to have produced reasonably realistic results, and it is felt that it is worth publishing in the FTM series as an interesting first attempt to deal with the problem from the local forecaster's point of view.

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# Forecasting the inland penetration of a sea breeze over Lincolnshire

by O. W. Brittain

## 1. Introduction

In an earlier paper[1] a relationship was found between the component, $V_g$, of the geostrophic wind perpendicular to the coast and the difference between $T_L$, the land temperature, and $T_S$, the sea temperature at the Outer Dowsing Light Vessel, for a sea breeze to reach Manby. An attempt to produce a similar relationship for a station further inland was not successful, so a sea breeze model was developed. Using this model and the relationship between $T_L-T_S$ and $V_g$ applying to Manby, the inland extent of the sea breeze may be found.

## 2. Observed features of sea breezes over Lincolnshire

The much simplified model largely follows from observed features of sea breezes over Lincolnshire, and the generally accepted theory of the generation of a sea breeze. Once suitable values of $T_L-T_S$ and $V_g$ occur, a low level flow from sea to land which forms part of the sea breeze circulation may develop. The value of $T_L$ considered must produce convection to 5000 ft or above over the land, for otherwise the sea breeze does not extend inland, although it may occur on the coast. The resulting flow at low levels from sea to land is initially across the pressure gradient established as part of the sea breeze mechanism, but veers as the coriolis force takes effect. If other forces are absent the path of the flow is a cycloid[2]. Before this is considered more fully, parameters which may affect the development of a sea breeze and likely relationships between these parameters need discussion.

It is to be expected that the strength of the sea breeze and its movement inland would depend upon:

a. The magnitude of the term $T_L-T_S$, with $T_L$ having a representative inland value.

b. The variation with time of $T_L$ within the sea breeze.

c. The offshore component $V_g$ of the geostrophic wind, and the corresponding component of the related surface wind, $V_o$.

d. The amount, depth and location of convective cloud.

It is observed that in general the magnitude of the term $T_L-T_S$ does not affect the inland penetration of a sea breeze which is often observed many miles inland on days when $T_L-T_S$ is small, and on other occasions confined to coastal areas when $T_L-T_S$ is large. However, in order for a sea breeze to be attained, a sufficiently high value of $T_L-T_S$ must develop to overcome the opposing offshore wind component $V_g$. The term $T_L-T_S$ does not appear to affect the strength of the sea breeze which varies very little from one occasion to another. However, when $T_L$ is increasing within the sea breeze, as in those developing early in the day, a stronger sea breeze results than when $T_L$ is falling rapidly, as in those which develop after the peak in solar heating.

It is found that the sea breeze develops irrespective of the position of cumulus on suitable sea breeze days, but on occasions of initially clear skies

/and

and light winds, developing cumulus is often first observed over the Lincolnshire Wolds. When large amounts of deep convective cloud form, the sea breeze sometimes fails to move very far inland, and on other occasions it moves erratically inland. Depth of convection, as long as it is sufficient to enable a sea breeze to form, does not appear to govern sea breeze speeds.

It has been found that the offshore component, Vc, of the observed surface wind over the land plays a significant part in determining the final inland extent of the sea breeze, as the pressure gradient which causes the sea breeze appears to have a constant value. It has not been possible to prove that this pressure gradient is constant but the results produced later are consistent with this assumption. The investigation therefore considers in detail the effect of the offshore component of surface wind opposing the motions of the sea breeze determined from the model.

3. A simplified model of the sea breeze

3.1. The symbols used, together with the sign convention, are set out below:-

x   Co-ordinate axis along the coast, positive from left to right when looking from sea to land.

y   Co-ordinate axis perpendicular to the coast, positive from sea to land.

$U_o$   Surface wind component along the x-axis resulting from the pressure gradient already present before the sea breeze commences.

$V_o$   As for $U_o$, but along the y-axis.

$V_g$   Component of geostrophic wind, along the y-axis, resulting from pressure gradient already present before sea breeze starts.

G   $\frac{1}{\rho} \frac{\partial p}{\partial n}$, where $\rho$ is the density of the air and $\partial p / \partial n$ is the pressure gradient, set up by inland heating, causing the sea breeze.

f   Coriolis parameter (= $0.4212\ hr^{-1}$ at $53^oN$).

$u_s$   Sea-breeze component in x-direction.

$v_s$   Sea-breeze component in y-direction.

$v_g$   Geostrophic wind corresponding to G, i.e. $v_g = \frac{G}{f}$

$v_o$   Surface wind corresponding to $v_g$

$\propto$   Direction of sea-breeze flow across the coast, measured anti-clockwise from the x-axis.

t   Time in hours after the start of the sea breeze.

/3.2.

3.2. The simplifying assumptions used in developing the model are as follows:

a. The sea breeze flow described above does not commence until convection to 5000 ft is present. It has been shown[1], that if convection fails to reach 5000 ft. the sea breeze does not develop regardless of magnitude of term $T_L - T_S$.

b. The pressure gradient set up at low levels as a result of inland heating is such that it would correspond to a geostrophic wind of 15 kt blowing parallel to the coast, i.e.

$$v_g = \frac{G}{f} = 15 \text{ kt}$$

which appears to be constant for all depths of convection and all values of $T_L - T_S$.

c. The ratio of observed surface wind to the geostrophic wind is 2/3, with no change of direction within the friction layer, i.e. $v_o = 10$ kt and is directed parallel to the coast. Otherwise, the effects of friction are neglected.

d. Pressure gradients aiding or opposing the sea breeze can be expressed as a mean value in terms of the surface wind which results from these pressure gradients.

e. Variations with latitude of the Coriolis parameter are ignored.

f. The sea breeze front originates on the coastline whether or not there is initially any offshore or onshore wind.

Assumption a is observed to be true and b is consistent with the results obtained using the present model. d is probably a reasonable assumption to make but where mean values of opposing effects are used minor errors of timing the onset of sea breezes and their limits of penetration can arise. The error introduced by assumption e is also small. These and the remaining assumptions c and f are apparently justified by the success of the model as assessed by use of the Heidke skill score[3].

4. <u>Theory of the model</u>

Gordon[2] has derived the equations of motion of an initially stationary particle which is suddenly subjected to a uniform horizontal pressure gradient acting in the y-direction (i.e. pressure decreasing as y increases).

If $u = v = 0$ at $t = 0$, then

at time t

$$u = \frac{dx}{dt} = \frac{G}{f}(1 - \cos ft)$$

$$v = \frac{dy}{dt} = \frac{G}{f}(\sin ft)$$

/where

where G/f is the geostrophic wind corresponding to the imposed pressure gradient. Applying these equations to the pressure gradient set up by inland heating to initiate the sea breeze, and considering the components of the resulting surface wind

$$u_s = v_o (1 - \cos ft) \qquad (1)$$

$$v_s = v_o \sin ft \qquad (2)$$

where $v_o = \frac{2}{3} v_g = \frac{2}{3}\frac{G}{f}$ (assumptions b and c of section 3). The surface component of the sea breeze perpendicular to the coast, $v_s$, is plotted as a function of time, t, in Fig. 1, assuming $v_o$ = 10 kt at latitude 53°N.

If, however, the particle is not stationary initially, but is moving in a uniform velocity field, the resultant motion of the particle is the vector sum of the initial motion and that due to the imposed pressure gradient. The resultant component perpendicular to the coast, $v_r$, is given by

$$v_r = v_s + V_o$$

$$= v_o \sin ft + V_o$$

If $V_o \geq 0$, the sea breeze will start to penetrate inland as soon as the necessary pressure gradient has been set up, i.e. at t = 0. If $V_o < 0$, i.e. the initial wind has an off-shore component, $v_s$ must increase until $v_s + V_o > 0$ before the sea breeze can begin to penetrate inland: let $v_s + V_o = 0$ at $t = t'$. Eq. 2 can then be written

$$-V_o = v_o \sin ft'$$

$$\text{or} \quad t' = \frac{1}{f} \sin^{-1}\left(-\frac{V_o}{v_o}\right) \qquad (3)$$

For values of $-V_o$ less than $v_o$, $v_s + V_o$ increases after $t'$, reaching a maximum at $\pi/2f$, and falling to zero at $t = \frac{\pi}{f} - t'$, the time at which inland penetration ceases. If $-V_o \geq v_o$, the sea breeze front cannot move inland.

Fig. 1 may be used to obtain the value of $t'$ for a given $V_o$: a horizontal line drawn at $v_s = -V_o$ intersects the curve twice, at points where $v_s = -V_o$, i.e. at $t'$ and $\frac{\pi}{f} - t'$ (7.5 - $t'$ hr at latitude 53°). For example, if $V_o$ = -5kt, the horizontal line is drawn at $v_s$ = 5kt, intersecting the curve at t = 1.25 hr (= $t'$) and at t = 6.25 hr (= 7.5 - $t'$).

The inland penetration of the sea breeze is assumed to be given by the displacement in the y-direction of the particle which starts to move inland from the coast at $t = t'$. At any time, t

/y

$$y = \int_{t'}^{t} (v_s + V_o)\,dt$$

$$= \int_{t'}^{t} (v_o \sin ft + V_o)\,dt$$

$$= \frac{v_o}{f}(\cos ft' - \cos ft) + V_o(t - t') \qquad (4)$$

Values of y for various values of $V_o$ (and hence of $t'$) are plotted as a function of t in Fig 2. The values of $V_o$ are indicated on the curves; the corresponding values of $t'$ are given by the intercepts on the t-axis. The distances of Binbrook and Scampton from the coast are denoted by the two horizontal lines: the intersection of the curves with theselines denotes the times at which the sea breeze front is expected to reach the two stations. It is apparent that the sea breeze will not reach Binbrook and Scampton if the offshore component of the surface wind is greater than 5 kt or 2½kt respectively.

The maximum distance inland to which the sea breeze penetrates is given by the value of y at $t = \frac{\pi}{f} - t' = (7.5 - t')$ hr. Substituting this value of t in Eq. (4)

$$y_{max} = \frac{v_o}{f}(\cos ft' - \cos(\pi - ft')) + V_o(\frac{\pi}{f} - t' - t')$$

$$= \frac{2v_o}{f}\cos ft' + V_o(\frac{\pi}{f} - 2t')$$

For $v_o = 10$ kt, $f = 0.4212\ hr^{-1}$

$$y_{max} = 47.5 \cos ft' + V_o(7.5 - 2t') \text{ nautical miles} \qquad (5)$$

Eq. 5 yields the line MN in Fig. 2, the y-values denoting the maximum inland penetration of the sea breeze for given values of $V_o$.

For example, the line RS shows that for $V_o = -4$ kt the sea breeze starts to move inland at t = 1 hr, reaches Binbrook at t = 4.6 hr, and attains its furthest inland position, 21 nautical miles from the coast, at t = 6.5 hr.

Finally, an estimate of the time at which conditions are first suitable for a sea breeze to occur, i.e. t = 0, may be obtained from Fig. 3, reproduced in a modified form from Brittain et. al[1]. It is the earliest time at which both the following conditions are fulfilled: a. the point representing $T_L - T_S$, the difference between the temperature of the air at screen level over the land and the sea temperature, and $V_g$, the off-shore component of the geostrophic wind, will lie within the "sea-breeze" area on the diagram; b. the values of $T_L$ will be sufficiently high to lead to convection to at least 5000 ft.

/5.

## 5. Some further features of the sea breeze

If $U_o = 0$, $V_o = 0$,

$$\alpha = \tan^{-1} \frac{v_s}{u_s} = \tan^{-1} \left(\frac{\sin ft}{1-\cos ft}\right) \qquad (6)$$

By differentiating $\alpha$ with respect to time

$$\frac{d\alpha}{dt} = -\frac{f}{2} \qquad (7)$$

Equation (7) implies that the rate of veer of wind within the sea breeze is constant for a particular latitude, and the negative sign arises because $\alpha$ becomes smaller as the Coriolis force takes effect. If $\alpha$ is plotted against time t a straight line results with $\alpha = \frac{\pi}{2}$ at t = 0 and in the geostrophic state $\alpha = 0$ at $t = \frac{\pi}{f}$. The sea breeze thus veers at $12^o$ per hour in latitude 53 N and observed values are close to this up to t = 6 hours. Beyond t = 6 hr it may be that frictional effects prevent a further veer to the geostrophic state which should occur at t = 7.5 hr, but the return to an offshore wind is usually observed as a sudden and marked veer.

## 6. Testing the model

The model was tested using data for the years 1963 to 1968. The method of selection of data differed slightly from year to year.

a. the data for 1963-4 were selected from past records and consist of a few obvious cases of sea breeze on occasions when $T_L - T_S$ was large and Vg was small so that the time of start of the sea breeze could be assumed to coincide with the first appearance of cumulus in the area;

b. for 1966-7, the data were mainly for occasions on which a sea breeze reached Binbrook;

c. for 1965 and 1968 the data cover most of the occasions on which a sea breeze could have started at the coast.

The time of start of the sea breeze, t = 0, was determined from Fig. 3. $V_o$ was obtained from the surface winds at Binbrook by resolving normal to the coast and averaging for the period t = 0 to t = 6 hr. or until the sea breeze reached Binbrook, whichever was the shorter. Knowing $V_o$, the appropriate curve was selected from Fig. 2: if the curve intersected the Binbrook or Scampton line the sea breeze was forecast to reach the station at a time given by the t - coordinate of the point of intersection.

Table I shows the contingency tables obtained for both stations, together with the skill scores, s*, and the percentage of forecasts correct. It should perhaps be emphasized that the results are obtained using actual, not forecast, values of the predictors (Vg, $T_L$, $T_S$, $V_o$).

/TABLE

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$$* \quad s = \frac{\text{Number of forecasts correct - number correct by chance}}{\text{Total number of forecasts - number correct by chance}}$$

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**TABLE I**

Binbrook

| | Sea Breeze Expected | Sea Breeze Not Expected | Total | |
|---|---|---|---|---|
| Sea Breeze Observed | 59 | 3 | 62 | Skill Score S = 0.65 |
| Sea Breeze not observed | 8 | 14 | 22 | Percentage correct 87% |
| Total | 67 | 17 | 84 | |

Scampton

| | Sea Breeze Expected | Sea Breeze Not Expected | Total | |
|---|---|---|---|---|
| Sea Breeze Observed | 30 | 5 | 35 | Skill Score S = 0.75 |
| Sea Breeze not observed | 4 | 33 | 37 | Percentage correct 87% |
| Total | 34 | 38 | 72 | |

The errors of timing the arrival of the sea breeze at Binbrook are shown in the first line of Table II: they show a bias towards positive errors (i.e. the sea breeze usually arrives later than forecast). The bias can be reduced by adding $\frac{3}{4}$ hr to the time of arrival as predicted by the model: this results in the distribution of errors shown in the second row of the table.

**TABLE II**

| Error (hr) | $-2\frac{1}{2}$ to $-1\frac{1}{2}$ | $-1\frac{1}{2}$ to $-\frac{1}{2}$ | $-\frac{1}{2}$ to $+\frac{1}{2}$ | $+\frac{1}{2}$ to $+1\frac{1}{2}$ | $+1\frac{1}{2}$ to $+2\frac{1}{2}$ | $+2\frac{1}{2}$ to $+3\frac{1}{2}$ |
|---|---|---|---|---|---|---|
| Before adjustment | 0 | 1 | 13 | 19 | 2 | 2 |
| After adjustment by $\frac{3}{4}$ hr | 0 | 8 | 22 | 5 | 1 | 1 |

The data in Table II refer only to the period since the anemograph was installed, hence the number of occasions is smaller than that given in Table I.

There are three main sources of error in predicting the time of arrival of the sea breeze at an inland station:

/a.

a. uncertainties in the estimation of the time of start of the sea breeze at the coast;

b. errors in $V_o$, particularly when the wind is not steady;

c. the occurrence of widespread convection cloud may influence the progress of the sea breeze front inland.

7. Examination of failures

Occasions when the method failed were fully investigated. In five cases at Binbrook no reason for failure was evident, but in four of these cases a likely cause would be failure to cross the Wolds.

The dates of these failures are as follows:

| | |
|---|---|
| 16 April 1965 | 20 May 1965 |
| 2 June 1966 | 19 June 1967 |
| 28 August 1967 | |

Other cases of failure at Binbrook are as follows:

1 June 1966 and 26 April 1968 Dry convection only. The sea breeze spread rapidly inland against a strong offshore wind, reaching Binbrook, although the forecasts indicated that it would not do so.

2 July 1967 The sea breeze was forecast to reach Binbrook but did not: $T_L - T_S = 3°C$ at 2100 GMT and as $V_g = 0$ this marked the end of the sea breeze. A feeble sea breeze reached Manby at 1930 GMT but it failed to reach Binbrook.

17 August 1965 The sea breeze reached Brigsley, Lincolnshire (12 miles inland and at the foot of the Wolds) instead of the 17 miles suggested by the model.

12 July 1968 The sea breeze, forecast to reach Binbrook, failed to move so far inland after encountering a marked trough. In general the sea breeze will not penetrate through a trough, but may make the trough more active.

26 May 1965 In this case it cannot be certain that the sea breeze was responsible for the light variable wind. This could equally be related to one of many showers in the area falling from cumulus with the tops at 11500 ft. With large amounts of deep convective cloud erratic movements of the sea breeze are sometimes observed, as was confirmed on this occasion by observations at Manby where the sea breeze alternated with offshore winds throughout the afternoon.

It will be noted that the total of failures at Binbrook is 11 which tallies with the first table of skill scores.

One case worthy of comment is that of 12 August 1968, an occasion with $V_o$ such as to make it a marginal case between occurrence and non-occurrence even on the coast. Thick industrial haze from Humberside factories formed into a black cloud with top estimated at 10,000 ft from the representative sounding. A few very large raindrops fell over Grimsby and it was necessary

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to use domestic lights during the mid-afternoon at Immingham a few miles away. The sea breeze could be seen clearly from Binbrook, but as the model suggests, better visibilities over the land gradually spread back to the coastal area.

The failures at Scampton were less easy to explain, and no definite reason for failure could be found on 8 occasions.

The dates are as follows:

| | |
|---|---|
| 7 July 1965 | 6 September 1965 |
| 13 September 1965 | 18 May 1967 |
| 11 July 1967 | 18 April 1968 |
| 25 April 1968 | 21 July 1968 |

On 27 August 1965 the sea breeze was forecast to reach Scampton, but a marked backing of the geostrophic wind after the sea breeze reached Binbrook resulted in a value of $V_o = -3$ kt (using Scampton winds), so that the sea breeze would not be expected at Scampton on this basis. On the remaining occasions the sea breeze was forecast not to reach Scampton; on 7 July 1965, 13 September 1965 and 25 April 1968 it is doubtful whether there were sea breeze at Scampton although they have been counted as such. The cases of 11 July 1967 and 18 April 1968 were very marginal ones.

The 9 failures at Scampton tally with the skill score table. On 12 occasions the office at Scampton was closed, hence the difference in the number of cases between the two stations.

## 8. Conclusions

The model, even with major simplifications, is in good agreement with observed features of the sea breeze, originating on the long relatively straight coastline of North Lincolnshire. It reveals several important features of the sea breeze motion over Lincolnshire, notably the effective constancy of the term G, and the importance of the mean value of the term $V_o$, rather than $T_L - T_S$, in determining the final position of the sea breeze front. The model also implies that there is no set direction for a sea breeze in the area considered, but that it varies with the initial wind field specified by $U_o$ and $V_o$, and upon the time elapsed since origination on the coast. It should be possible to find forecasting criteria in other parts of the country, firstly by finding the relationship between the terms $T_L - T_S$ and Vg, the limiting value of Vg above which no sea breeze will develop, then by investigating which values of $V_o$ permit a sea breeze to reach the local station. Where the coastline is irregular or curved, several parts of the coastline may have to be considered as possible areas of origin of the sea breeze. In these locations values of $U_o$ as well as $V_o$ will be important. Although it will not be possible generally, to forecast $V_o$ with the degree of accuracy demanded by the model, a useful guide to the likely penetration limits of the sea breeze may be obtained.

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9. Acknowledgements

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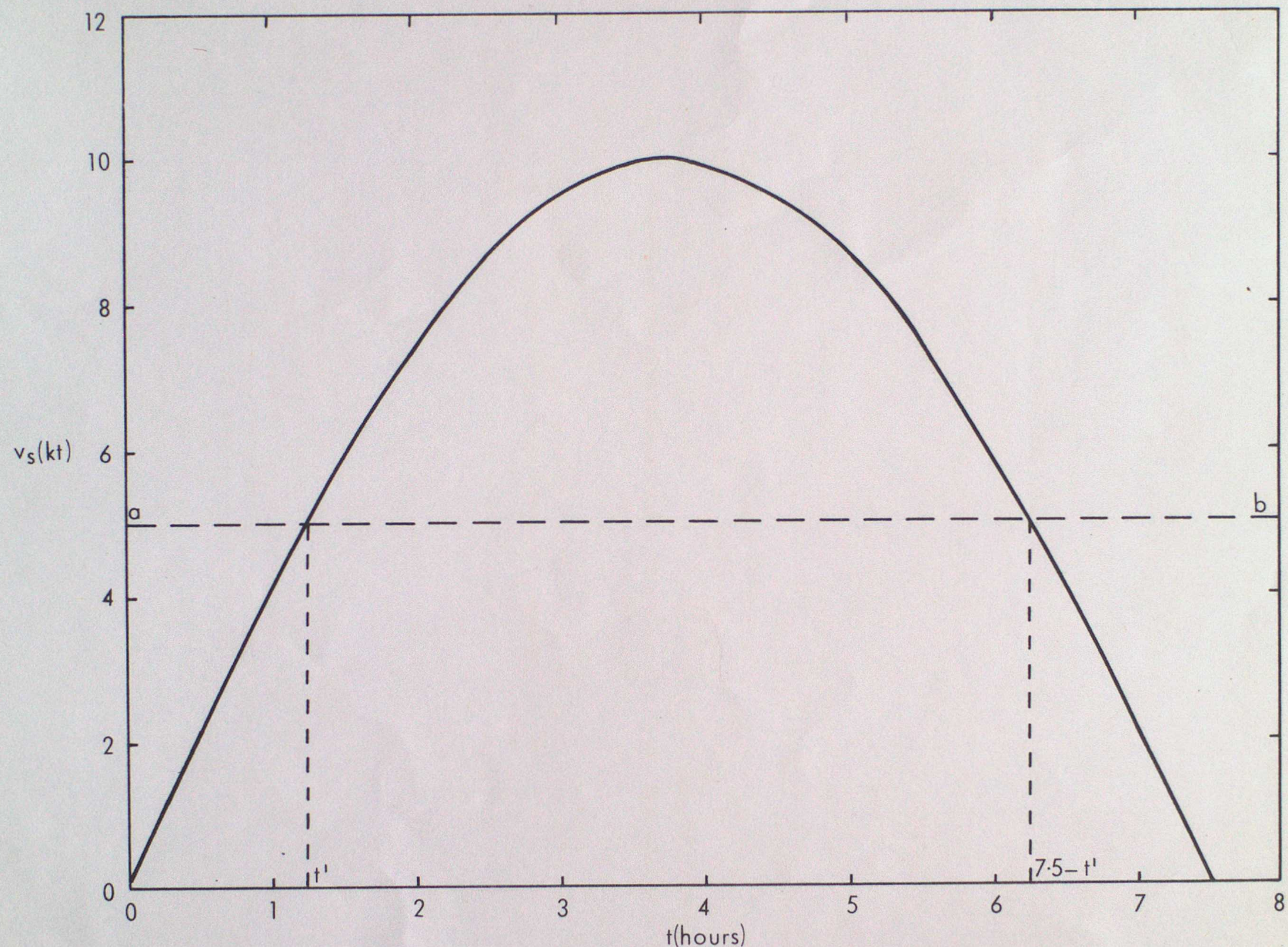


Fig 1 Variation of $v_s$ with time after start of sea breeze at coast; determination of t'

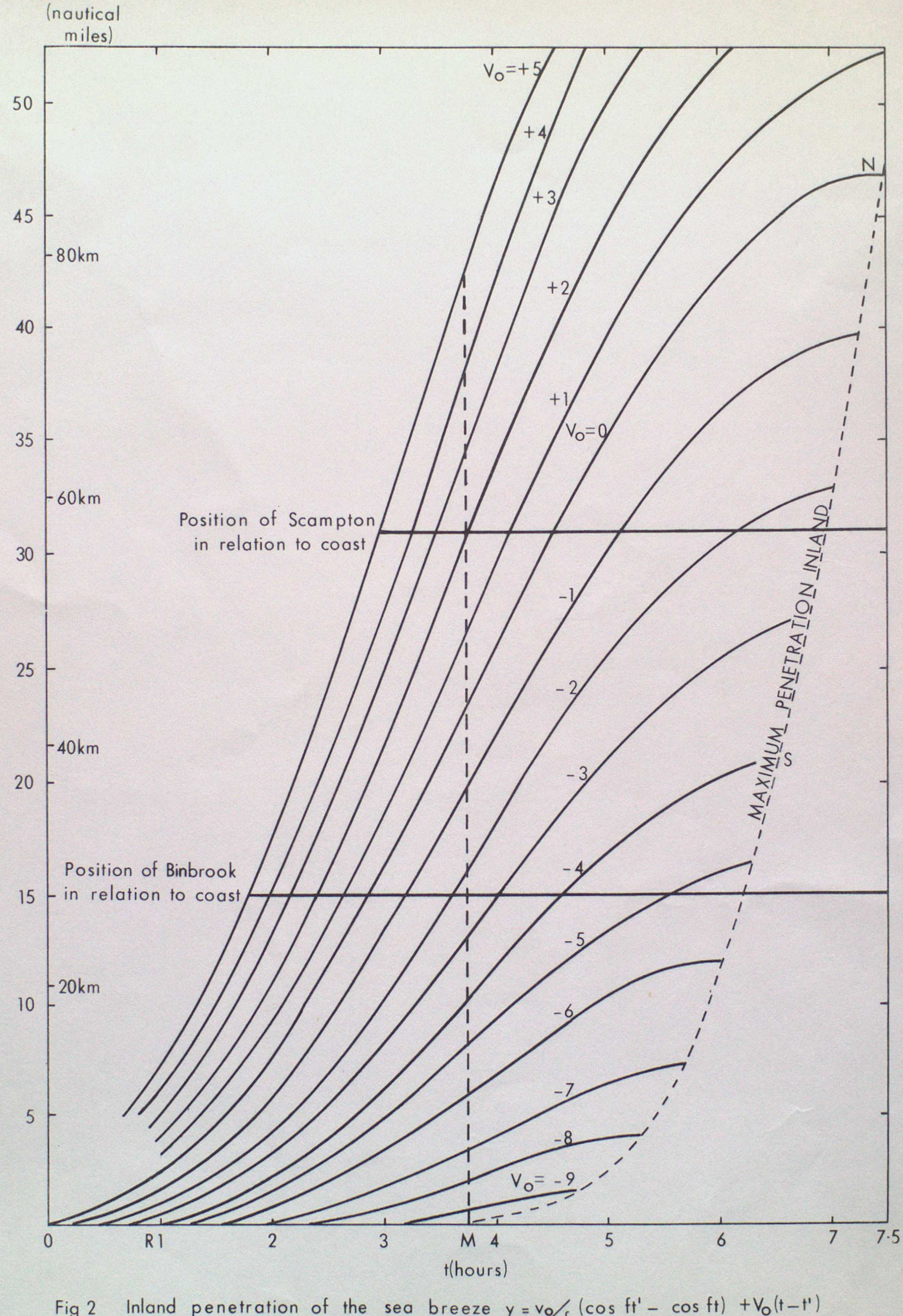


Fig 2 Inland penetration of the sea breeze $y = \frac{v_o}{f}(\cos ft' - \cos ft) + V_o(t - t')$

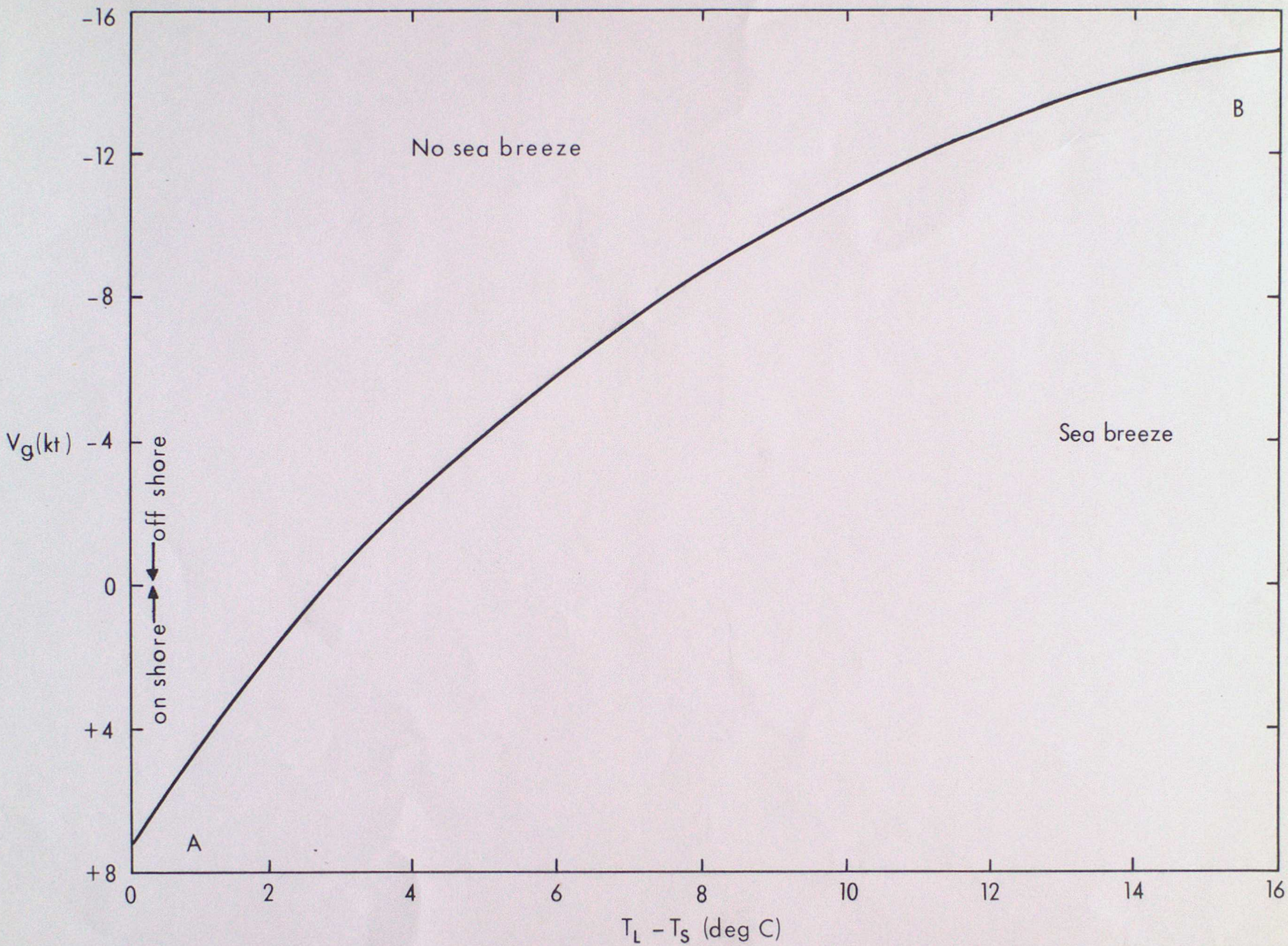


Fig 3 The relationship between $T_L - T_S$ and $V_g$ for a sea breeze to reach Manby

## FORECASTING TECHNIQUES MEMORANDA

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