F.T.B.M.12

METEOROLOGICAL OFFICE

FORECASTING TECHNIQUES BRANCH

MEMORANDUM No. 12

ON SEA-BREEZE FORECASTING TECHNIQUES

June 1966

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ON SEA BREEZE FORECASTING TECHNIQUES

EDITED BY

W.D.S. McCAFFERY

JUNE, 1966

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PREFACE

This memorandum contains three articles on the sea breeze:

1. The sea breeze at Lasham by J.E. Simpson
2. A method of forecasting sea breezes at Manby by O.W. Brittain
3. Interim report on sea breeze investigation at Scampton (near Lincoln) by E.C. Pepperdine.

These articles are referred to in this memorandum as Articles 1,2 and 3.

Article 1, which was presented by the author at the 10th OSTIV Congress held at South Cerney in June, 1965, is reproduced from the Swiss Aero Revue. It is included here to facilitate reference to it by forecasters who may wish to consider ideas discussed in this memorandum, test suggested techniques for forecasting the sea breeze or evolve a technique for use at their own station. Acknowledgement is made to the author, OSTIV and the Swiss Aero Revue for their kind permission to reproduce the article.

Articles 2 and 3 are in the nature of interim reports on work done by two forecasters, one at Manby and the other at Scampton. The reports indicate how far the authors have gone towards:

1. Understanding the nature of the sea breeze as it affects their own station
2. developing techniques for forecasting the onset and character of the sea breeze, the changes it may bring and its final decay.

The final part of this memorandum reviews some characteristics of the sea breeze and discusses the techniques described in the articles referred to above as well as other published and unpublished techniques used by forecasters in the British Isles. It is hoped that forecasters will be encouraged to examine cases of sea breeze as they occur, to record, classify and analyse relevant details and to test what techniques are available, adapting them where possible to their own locality and requirements.

Met O 8b
June, 1966

The sea-breeze at Lasham

By John E. Simpson, Lasham Gliding Centre, England.

Presented at the 10th OSTIV Congress, South Cerney, England, June 1965

(From Swiss Aero-revue, Nov. 1965)

1. Tracking the fronts

During the summers of 1962-3-4 a special series of observations has been made, based on the Lasham Gliding Centre, to try and find out more about the behaviour and structure of the sea-breeze front as it travels across Hampshire.

There is nearly always a rise in dewpoint at the passage of the seabreeze front (1), so nine pairs of thermographs and hygrographs were set up, enabling dewpoints to be calculated on likely days. Using discontinuities in these dewpoint records and Met. Office records it was possible to track the movements of the fronts inland in some detail.

Fig. 1 shows the position of the stations and the average isochrones for the 16 fronts which reached Lasham in 1962-3 from mid-April to mid-August. The fronts in 1964 formed a similar pattern.

Most of the fronts showed a gradual increase in speed of advance inland from 3 knots or less near the coast to 7 or 8 knots in the later stages. Several were detectable as far as Greenham Common and Reading, 20 miles beyond Lasham.

Although the average isochrones have necessarily appeared as smooth curves, individual fronts could often be seen to be advancing at different rates in different sections.

As well as the haze and clouds which mark these fronts (2), swifts have also served as markers of the rising air. On 13 May 1961 and 26 May 1963, I was able to make soaring flights along the sea-breeze front at about 2000 feet by following groups of swifts apparently catching their insect food in the lift.

2. Soaring Conditions

Soaring has been carried out near the front, both on occasions (a) when it was almost stationary, and (b) when it was moving inland at a speed comparable with the sea-breeze itself.

(a) On 3rd June 1962, the task in the National Gliding Championships was a 300 km triangle, and the first turning point was at Cerne Abbas, only 12 miles from the South Coast. From 1200-1300 GMT the sea-breeze front was in the neighbourhood of this turning point. The wind inland was NE about 12 knots, and to the south of the line it was SE, 8 knots. All pilots reported masses of confused cloud, and many had difficulty with low cloud obscuring the turning point. The base of the cumulus to the north was about 4500 feet; at the front which was marked by intermittent

/patches

patches of low streamer cloud, the base was about 2500 feet, with some patches even lower. It was cloudless well to the south of the frontal area. The best lift anyone found was 5 knots, by circling in and out of the cloud on the landward side. The average of 12 reports gave $2\frac{1}{2}$ knots, so the air was rising at about 4 knots (2 m/sec).

Near Cerne the front as a whole was not moving fast, but pilots reported local advances. At one time bars of cloud were visible, with cumulus-like lumps embeddied in them, both the tops and the bases of this cloud were lower than those of the inland cloud.

15 miles east of Cerne, curtain clouds were visible, and N. Goodhart rejoined the front 3 miles north of Blandford at about 2800 feet and circled in a narrow band of lift of 4 knots in and out of the cloud. On reaching 4000 feet he was able to fly straight at 60 knots for eight miles with little loss of height. The patches of cloud marking the front were by then getting less frequent, so he headed more northerly towards occasional cu, still visible there. Most pilots needed to fly north nearly as far as Salisbury to find lift, and there was little cloud from there to Lasham. The last pilot flew past Lasham at 1610 GMT, 20 minutes before the sea-breeze arrived there.

Lift was found at another almost stationary front on 5 August 1962. This front remained for over half an hour across Lasham airfield; it also just reached S. Farnborough, where there were at first some interesting reversals of wind direction, with associated dewpoint changes. At Lasham several pilots investigated the rising air, which they found in narrow strips parallel to broken sections of low "curtain cloud". There were downcurrents to the north and the south of this line. Air was rising at about 4 knots, and climbs were made to 4000 feet; winds to north of the front were WNW, 10 knots, and to the south were SW, 15 knots.

(b) The front passed Lasham at 1730 hours on 8 June 1962, travelling steadily at about 6 knots. This was a day of light NE winds. Two pilots found severe turbulence at 900 feet above ground north of Winchester, and made climbs to 2000 feet into a line of steady lift. North of Lasham there was a large area of lift; no clouds at all at that time of day.

Another large area of lift associated with a comparatively fastmoving front was found on 11 June 1963; this extended over an area two miles wide in which height could be maintained at 2000 feet.

3. Cross-section Flight

A flight was made through a sea-breeze front on 11 Aug. 1963 in an Auster aircraft, fitted with an electrical psychrometer. The track was the line from Lasham to Thorney Island on the coast, at right angles to the front. Traverses were made at five different heights up to 3500 feet.

/Fig. 2

Fig. 2 shows isopleths of humidity mixing ratio, and the two types of cloud visible. There was solid line of cumulus cloud, with base just below 4000 feet in a line parallel to the coast and some isolated wisps at about 2000 feet. There was also a line of haze stretching up to the wisps from the ground.

Fig. 3 shows the temperature at Sections AA ("land-air") and BB ("sea-air") and the 1140 ascent at Crawley. North of the front the wind was 280°, 10-15 knots and to the south, it was 240°, 15 knots.

On this occasion it was not possible to measure the strength of the upcurrents, but it does seem likely from the diagram that the solid line of cloud was formed by the ascent of land-air, and that the wisps and haze were at the front of the sea-air which was being swept upwards and back towards the sea.

4. A Sea-breeze "Index"

A method of forecasting the sea-breeze at Thorney Island on the coast has been described on the basis of the forecasted 3000 feet wind and the expected excess of the land temperature over that of the sea (3). A sea-breeze at Thorney Island can be said to be a necessary condition for one at Lasham (except on the rarer occasions when it comes across London). Extension of the same principle to Lasham, i.e. with less winds at 3000 feet and greater temperature excesses has shown no consistent results. Whether the sea-breeze will progress inland depends on many other factors. For example, in 1962 at least 28 sea-breeze days were observed on the coast, of which only 8 reached Lasham. As well as the wind-strength and the sun's heating during the day, an important factor is naturally the depth of convection. Tephigrams for Lasham on sea-breeze days show an average inversion height of 4000 feet on NE days and 6000 feet on W days.

The most effective "index" for a sea-breeze arrival at Lasham so far has turned out to be the lowest value of the relative humidity reached during the day. Fig. 4 shows points plotted for days with a reasonable amount of sun-shine, when soaring was possible at Lasham. The offshore wind U has been plotted as the average of 5 Met. Office stations at 1200 GMT and relative humidity as the average from 5 hygrograms, including Lasham. The sea-breeze appears most likely for winds less than 10 knots and when the relative humidity falls below 40%.

A low relative humidity may be expected to be related to heating from the sun and also depth of convection, and this index turns out to be a very easy one to work in practice. On a good thermal day there is a simple relationship between the relative humidity at any time and the height of the convective cloudbase, so a practical rule-of-thumb for glider pilots is "on a good thermal day, when the wind is less than 10 knots, a sea-breeze

/front

front is likely to reach Lasham if cloud-base is at 5000 feet or higher".

5. Time-lapse film

About 150 feet of 16 mm time-lapse colour film shows cloud-forms at the sea-breeze front on days in 1962-3.

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(1) Peters, S.P., 1938: Sea Breezes at Worthy Down, Winchester. Prof. Notes, M.O. London, Vol. 6, No. 86.

(2) Wallington, C.E., 1959: The structure of the sea-breeze front as revealed by gliding flights. Weather. Vol. 14, p.263.

(3) Watts, A.J., 1955: Sea breeze at Thorney Island. Met. Mag. London. Vol. 84, p.42.

The sea breeze at Lasham

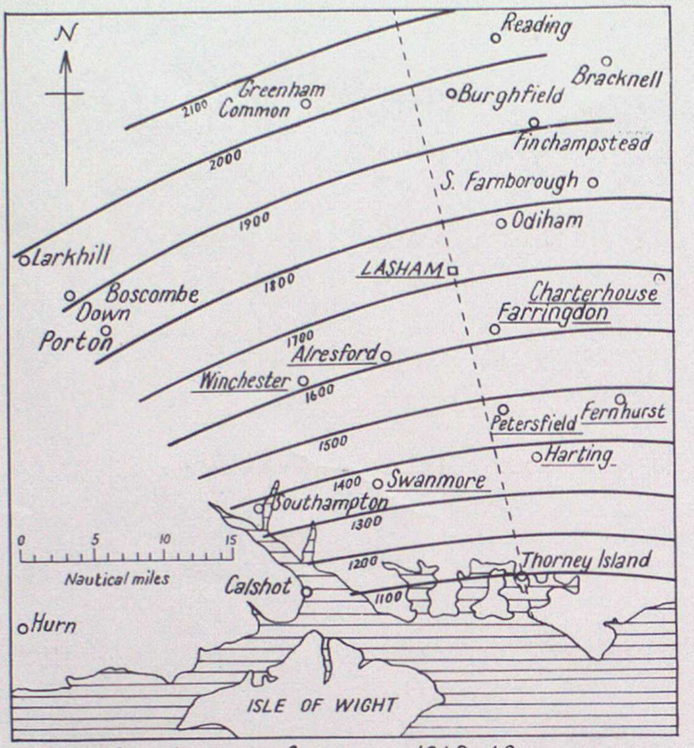

Fig 1. Sea-breeze fronts 1962-63

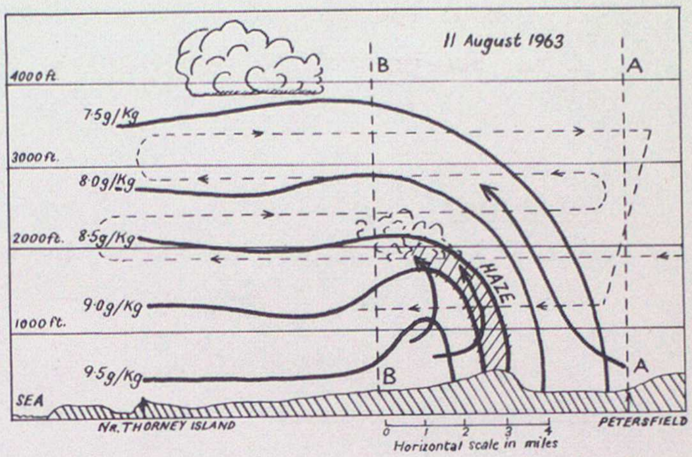

Fig 2. Moisture lines in section N-S of sea-breeze front

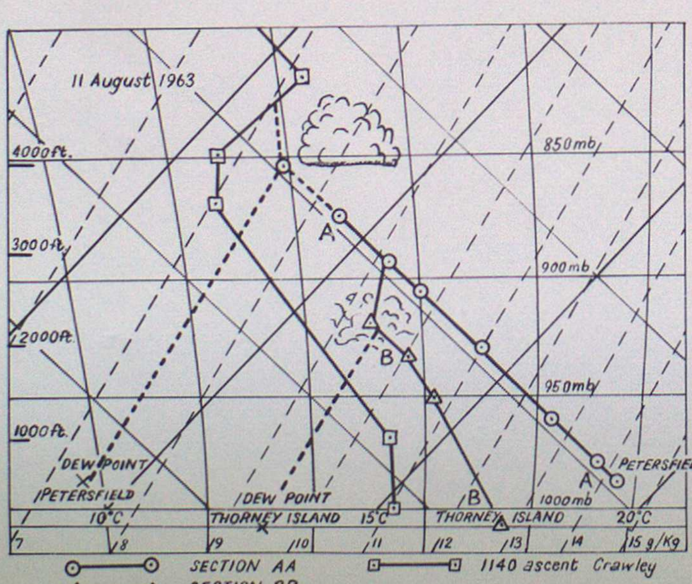

Fig 3.

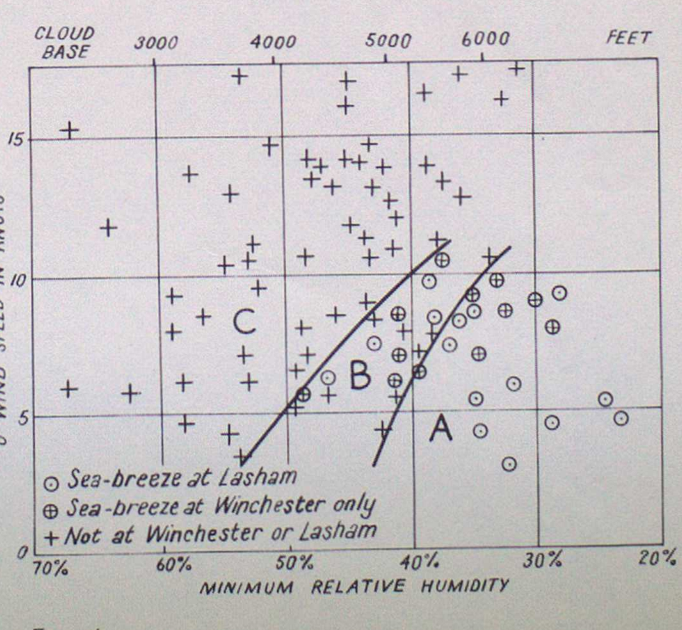

Fig 4.

A METHOD OF FORECASTING SEA BREEZES AT MANBY

by

OWEN W. BRITTAIN

INTRODUCTION:

The airfield at Manby, lying six miles inland from the Lincolnshire coast and three miles from the foot of the Lincolnshire Wolds, is affected by sea breezes between spring and late summer. A method of forecasting the incidence of the sea breeze at Manby has been devised, the information being derived from hourly observations at Manby, U.K. hourly facsimile charts and values of sea temperature from the Humber lightship. A knowledge of whether or not a sea breeze will affect a station is essential in deciding whether to forecast showers or not, or low stratus and fog spreading in from the sea. On many occasions a sea breeze can quicken the formation of radiation fog the following night.

DESCRIPTION:

The investigation set out to relate the arrival or otherwise of sea breezes at Manby with the difference between land and sea temperatures, and the component of gradient wind normal to the coast line. It was also intended to take account of an observed fact that a sea breeze rarely, if ever, reaches Manby until convection cloud has formed and grown to at least 5,000 feet.

Data used were as follows:

1. The Manby surface air temperature (T_L) and dew point (T_D).
2. The sea surface temperature (T_S).
3. The offshore component of gradient wind (V_O) obtained by resolving the gradient wind in the direction 240-060 deg., perpendicular to the Lincolnshire coast.

Fig. 1 is a scatter diagram of values of $T_L - T_S$ and V_O including all occasions when it was found from the Tephigram that convection extended past 850 mb.

Initially two types of occasion were plotted on Fig. 1, for days when $T_L > T_S$:

1. Occasions when sea breeze did not occur at Manby.
2. Occasions when sea breeze did occur at Manby.

At this stage, the line AB on Fig. 1 was found to provide a reasonable separation between occasions when a sea breeze never occurred at Manby and a mixed group of both occurrence and non-occurrence. It was further observed that in this latter group on occasions when a sea breeze failed to arrive at Manby large Cumulus cloud was seen to have developed between Manby and the coast.

/The

The entries on Fig. 1 have therefore been grouped to show:

above line AB

1. occasions when sea breeze never occurred at Manby

and below line AB

2. occasions when sea breeze did occur at Manby
3. occasions when sea breeze might have been expected at Manby but failed to occur and convection cloud was observed between Manby and the coast.

These three types of occurrence have been given separate symbols on Fig. 1.

As observed from Manby, on occasions of type 3, brilliantly blue sky can be seen beyond the Cumulus lying between Manby and the coast. The cumulus later moves inland, followed by the clear skies, suggesting the movement inland of cumulus forming at a sea breeze front.

In order to emphasize the importance of the convective process in a sea breeze circulation when a sea breeze spreads inland, Fig. 2 was drawn. All the occasions were days when either wet convection was impossible, or it failed to reach 850 mb. The occurrence or otherwise of the sea breeze reaching Manby was entered as on Fig. 1 so that Fig. 2 makes it clear that a sea breeze does not reach Manby on these occasions nor is there likely to be a penetration inland of a sea breeze between Manby and the coast. The one case of actual sea breeze on Fig. 2 was one in which wet convection extended to about 4800 feet, which was therefore a very border line case. The line AB on Fig. 2 is simply AB transferred from Fig. 1 for purposes of comparison.

Fig. 3 the synoptic chart for 1300 GMT, 29th March 1965, is produced as an example of the non arrival of sea breeze at many near coastal stations on a day of relatively high surface temperatures and no convection cloud. The tephigram for Aughton for this occasion (Fig. 4) confirms that wet convection was impossible. The sea temperature off the east coast was about 6 deg. C.

Some further sea breeze features noted during the investigation were as follows:

1. The sea breeze sets in initially from 060 deg. at about 10 Kt., if gradients are light. More often it is a resultant of the sea breeze effect and the expected surface wind from the gradient, if this is appreciable, but with only a small offshore component. Some hours later the observed wind usually blows from 130 deg., the favoured direction at Manby for a well developed sea breeze, due to geostrophic effect.

2. The strength of the sea breeze is not governed by the value of $T_L - T_S$, as was found by Watts (1) in an earlier investigation.

/3.

3. Sea breeze can arrive at Manby after the maximum temperature is reached, especially if a shift of gradient lowers the offshore component.

4. A few pilot balloon observations at Manby have indicated the top of a sea breeze between 1,000 and 2,000 feet. This confirms a recent finding by D.J. Ride (2).

5. The sea breeze ceases when $T_L - T_S = 2.8$ deg. C. for light gradients or when the component V_o becomes too great for the existing values of $T_L - T_S$.

USE OF THE DIAGRAMS

The suggested procedure is as follows:

1. If convection to 5000 feet is expected, forecast the gradient wind component V_o at the expected time of reaching T_C, the land temperature to produce convection to 5000 feet. If convection to 5000 feet is not expected, forecast no sea breeze.

2. Forecast values and times for T_L(max) and T_C and obtain T_L(max) $-T_S$ and $T_C - T_S$. Also forecast a value of V_o for T_L(max) assuming no reduction due to sea breeze effects.

3. Apply to Fig. 1 to obtain sea breeze expected or not expected. If T_C-T_S is below AB, this is the temperature difference for initiating sea breeze. If T_C-T_S is above AB, but T_L(max) - T_S is below AB, then a new time and value for T_L ($>$ T_C) can be found that brings T_L-T_S and V_o to AB. The earliest time of the arrival of the sea breeze can thus be found.

4. Forecast when $T_L - T_S = 3$ deg. C. for end of sea breeze, or occasionally, when V_o is increasing, obtain from graph a value of T_L-T_S that with V_o is near AB.

CONCLUSION

Forecasting the onset of a sea breeze remains a local problem. However, rules like the above and a different curve AB can be produced for any station some miles inland. The main difficulty is forecasting accurately the gradient wind, especially around SW where at Manby the offshore component is greatest. With these directions however, sea breeze is frequently delayed by cumulus developing between Manby and the coast, and no successful method of dealing with these cases has yet been found.

ACKNOWLEDGEMENTS:

Grateful thanks are due to the staff at Manby for valuable advice and criticism.

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(1) WATTS, A.J. Sea breeze at Thorney Island. Met. Mag., London 84, 1955, p.42.

(2) RIDE, D.J. A Discontinuity in Surface Wind arising from Differential Heating. "Weather" July 1965.

January, 1966

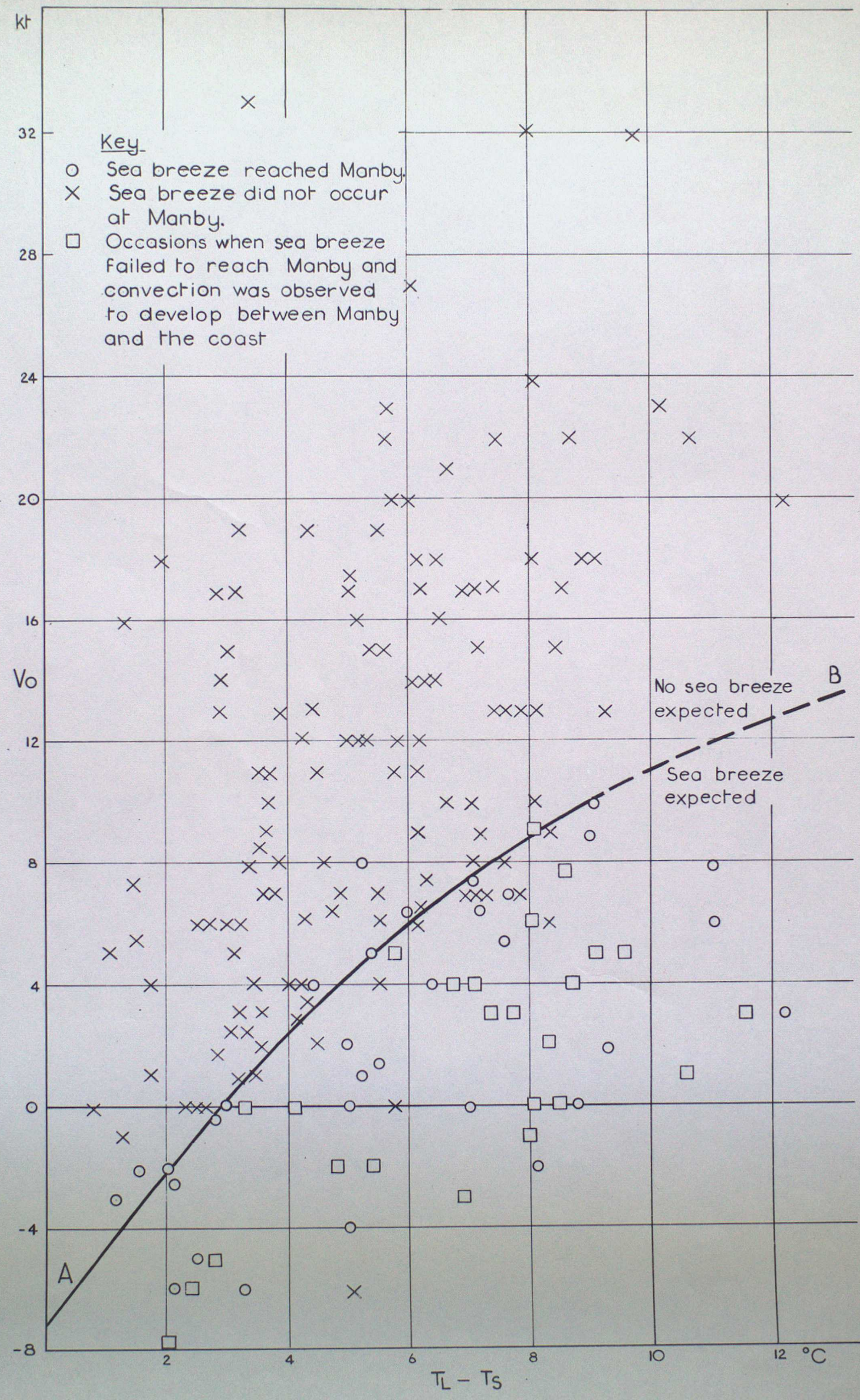


Figure 1. Graph of land-sea temperature excess and offshore component of gradient wind. Convection to 5,000 ft or above.

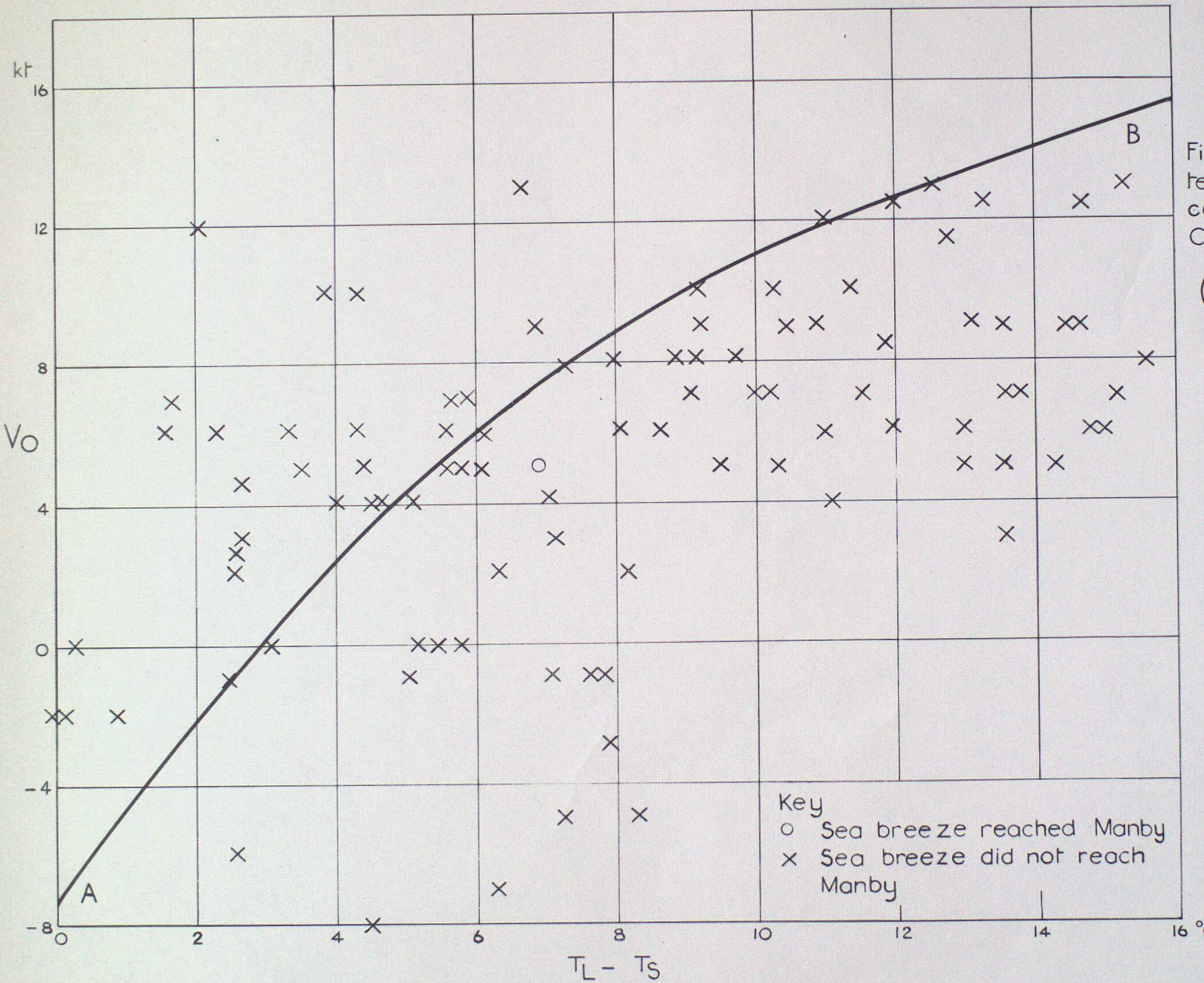


Figure 2. Graph of land-sea temperature excess and offshore componet of gradient wind. Convection to less than 5000 ft.

(AB is curve AB reproduced from Figure 1.)

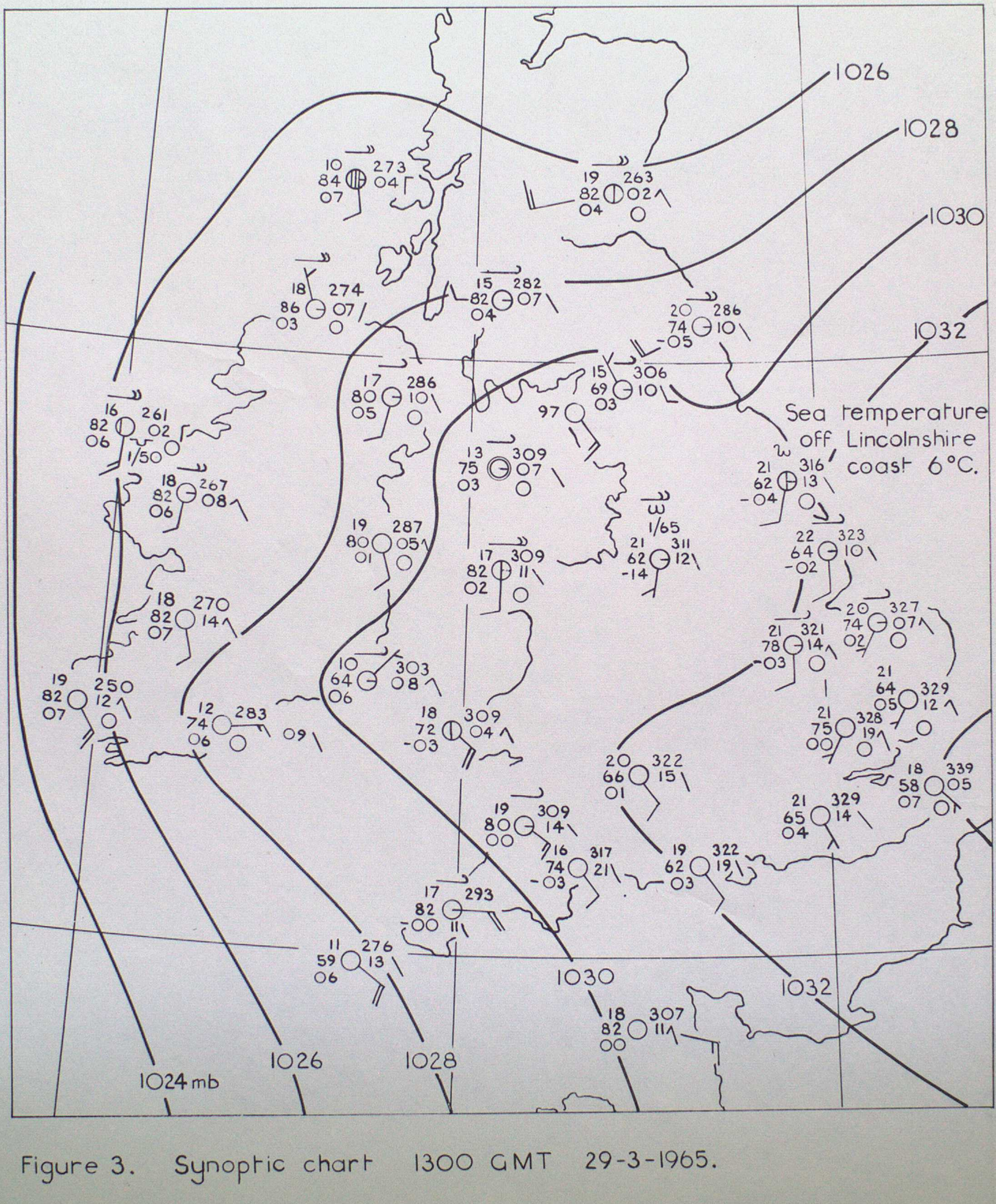


Figure 3. Synoptic chart 1300 GMT 29-3-1965.

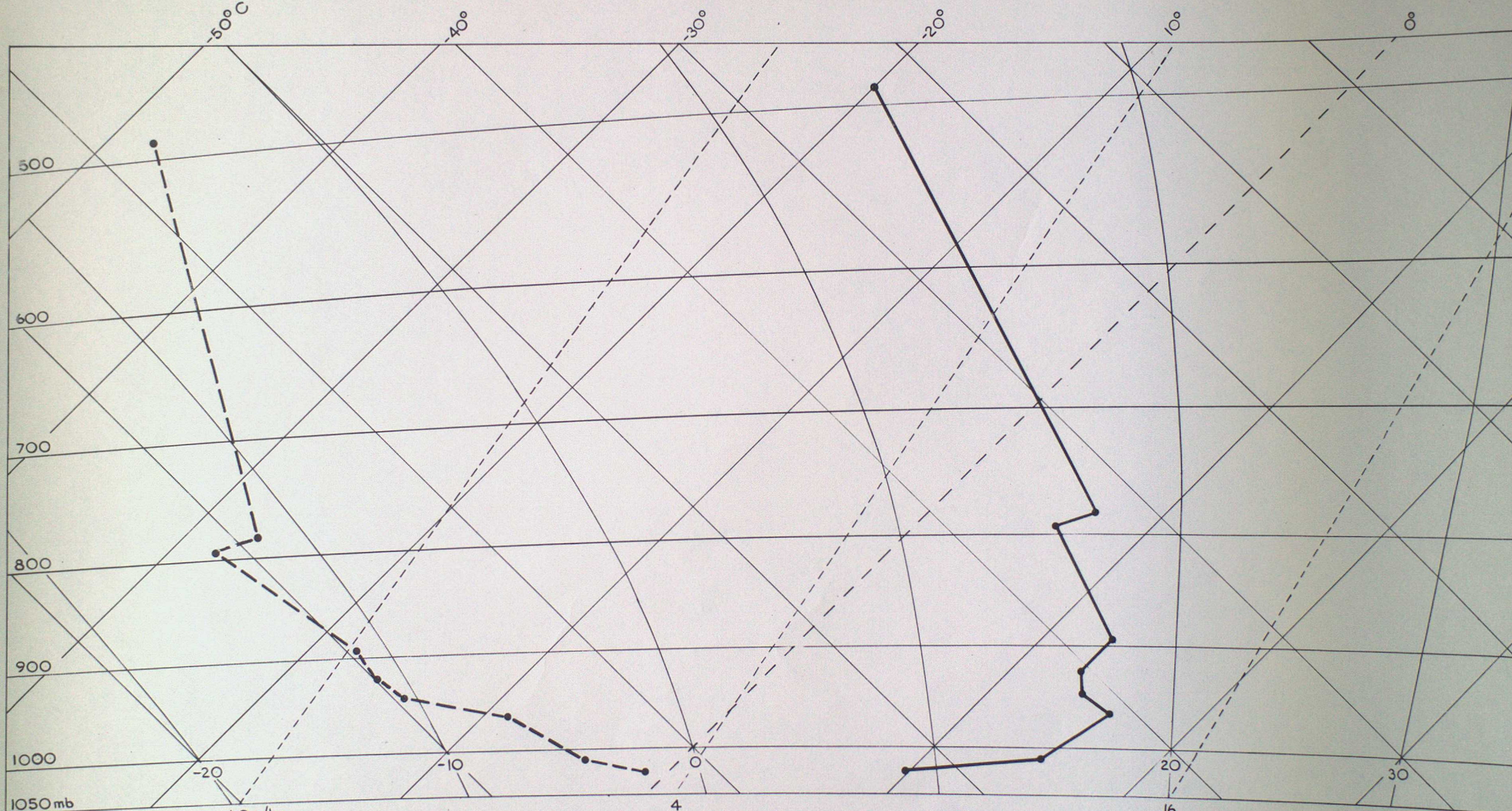


Figure 4. Aughton 0000 GMT 29-3-65. Dry bulb •——• Dew point •- - -•

Interim Report on Sea Breeze Investigation at Scampton (Near Lincoln)

by

Ernest. C. Pepperdine

INTRODUCTION

A sea breeze at Scampton, as elsewhere in Lincolnshire, sometimes arrives as a simple change of wind direction and entails nothing more than a possible change of runway. At other times it arrives as a line of showers followed by a dramatic clearance of cloud. Usually the air behind the sea breeze front is colder and has a higher fog-point than that ahead. On rare occasions the sea breeze carries a layer of low stratus inland apparently against the surface flow.

The sea breeze season is mainly April to September, and in that season the forecaster has to answer, early in the day, one main and two supplementary questions:-

(1) Will a sea breeze reach Scampton?

(2) What time will it arrive, and

(3) When will the gradient/land breeze replace it?

BASIS

In an attempt to provide a basis for answering these questions a record has been maintained since July 1961 of cases when a sea breeze was, early in the day, considered in the local forecast. The premises for the investigation were basically:-

(i) If the land to sea component of the surface wind exceeds a critical speed then a sea breeze is impossible.

(ii) For the air to move from sea to land some air must be extracted (presumably vertically) from the lower layers overland - hence convection is a likely pre-requisite of a sea breeze.

(iii) The pressure overland will not be relatively low until the land temperature exceeds that over the sea.

Before discussing the results of the investigation it is opportune to record further details of the sea breeze mechanism.

In a synoptic situation with no initial pressure gradient the sea to land gradient developed by diurnal heating will produce a flow perpendicular to the coast. If this flow continues uninterrupted the surface wind (in the northern hemisphere) will turn to the right i.e. the sea breeze will gradually veer during the day.

On the more usual synoptic occasions with some initial pressure gradient the resulting surface wind will be made up of two separate components - the gradient produced surface wind plus the sea breeze component appropriate to the time of day. These latter components will be partially dependent on the time the sea breeze started to flow across the coast, but experience suggests that over Lincolnshire they are of the order of:-

0900	040/10	1200	060/12	1500	070/15
1800	090/12	2100	120/06	(time GMT)	

/RESULTS

RESULTS With regard to premise (i) the appropriate surface wind would be that which would be produced by the gradient wind at the time the sea breeze was about to start, but how is one to be sure that this wind has not already been affected by some diurnal variation (katabatic, sea breeze etc)? To minimise this doubt it was decided to use the reported surface wind at the time of minimum diurnal variation, and this was assumed to be 0900 GMT. By plotting 0900 GMT surface winds for Scampton on a hodograph it was found that no sea breeze affected the station if the seaward component (the coastline is orientated 340/160) exceeded 7 or 8 knots. The critical line is shown on Figure 1 which is a copy of a standard hodograph with the speed scale doubled. It should be noted that winds are plotted on the diagram 'straight', and not as vectors e.g. a SW-ly surface wind is entered in the SW quadrant.

The curves in the critical line have been deliberately introduced to allow for distortion of the actual surface wind by local terrain. With winds in excess of those shown the maximum temperature is unlikely to rise high enough to produce a sea breeze and even if it did this sea breeze would have a relatively small effect on the surface wind.

To follow up premise (ii) the time of first formation of cumulus was logged, and it was found that a sea breeze rarely occurred at Scampton if Cumulus had not formed by 0900 GMT. More detailed analysis showed that most of the exceptions to this rule were occasions when convection took place by 0900 but the air was too dry to produce cloud. It was also noted that most of the occasions when Cumulus formed before 0900 GMT (with surface wind favourable) but no sea breeze arrived were cases when convection was particularly vigorous and cumulus tops exceeded 12,000 ft. It is suggested that on these occasions sufficient surface air is extracted a few miles inland to maintain a self-balancing coastal sea breeze without the front moving further inland. Thus a line of showers persists parallel to the Wolds and usually along their eastern slopes. Usually, as convective activity decreases in the late afternoon this line of showers begins to move inland very slowly, but too late for it to arrive at Scampton before the sea breeze energy is completly dissipated.

Investigation of premise (iii) led to a round figure of 10 degrees Fahrenheit (equals 5 deg C.) as a critical land over sea excess temp necessary to push the sea breeze inland to Scampton.

Since 0900 GMT is rather late for local area forecast purposes a relationship between the 0300 GMT gradient wind and subsequent sea breeze was sought. The resultant critical line is shown at Figure 2.

If the 1200 GMT gradient can be forecast reliably then this will be a better value to use on Fig. 2, but failing this the 0300 GMT actual gradient gives reasonable forecast success, although less successful than the 0900 GMT surface wind.

/RULES

<u>RULES</u> The 'rules' for forecasting the arrival of a sea breeze at Scampton are therefore:-

Rule 1. 0900 GMT surface wind (or 0300 GMT gradient wind) must lie to NE of critical line on Fig. 1 (or Fig. 2).

Rule 2. There must be convection by 0900 GMT.

Rule 3. Cumulus tops must not exceed 12,000 ft.

Rule 4. Expected maximum temperature must exceed 0600 GMT sea-temp at the Humber Light Vessel (station 398) by at least 5 deg. C.

<u>CROSS-CHECK</u> A retrospective check on the period 1/5/64 to 31/8/64 gave the following result. There were 47 days when a sea breeze would have been considered possible at 0900 GMT. Using the above rules (Fig. 1 only) the forecast would have been correct on 44 occasions.

<u>INVESTIGATION CONTINUES</u> Satisfactory answers to the two supplementary questions listed in the introduction have not been found. For question 2 correlations between time of arrival of sea breeze and time Scampton temperature reaches sea-temperature or reaches 5 deg. C excess have been sought in vain.

Similarly the strength of the land to sea component as a delaying factor has been tried without success.

Success in forecasting the period of persistence of the sea breeze has proved equally elusive. It is, in any case, difficult to define the actual time of cessation since the sea breeze/surface wind often falls to light and variable and therefore intermittently SE-ly until well into the night. However, for this same reason, cessation time is of little importance operationally.

March, 1965

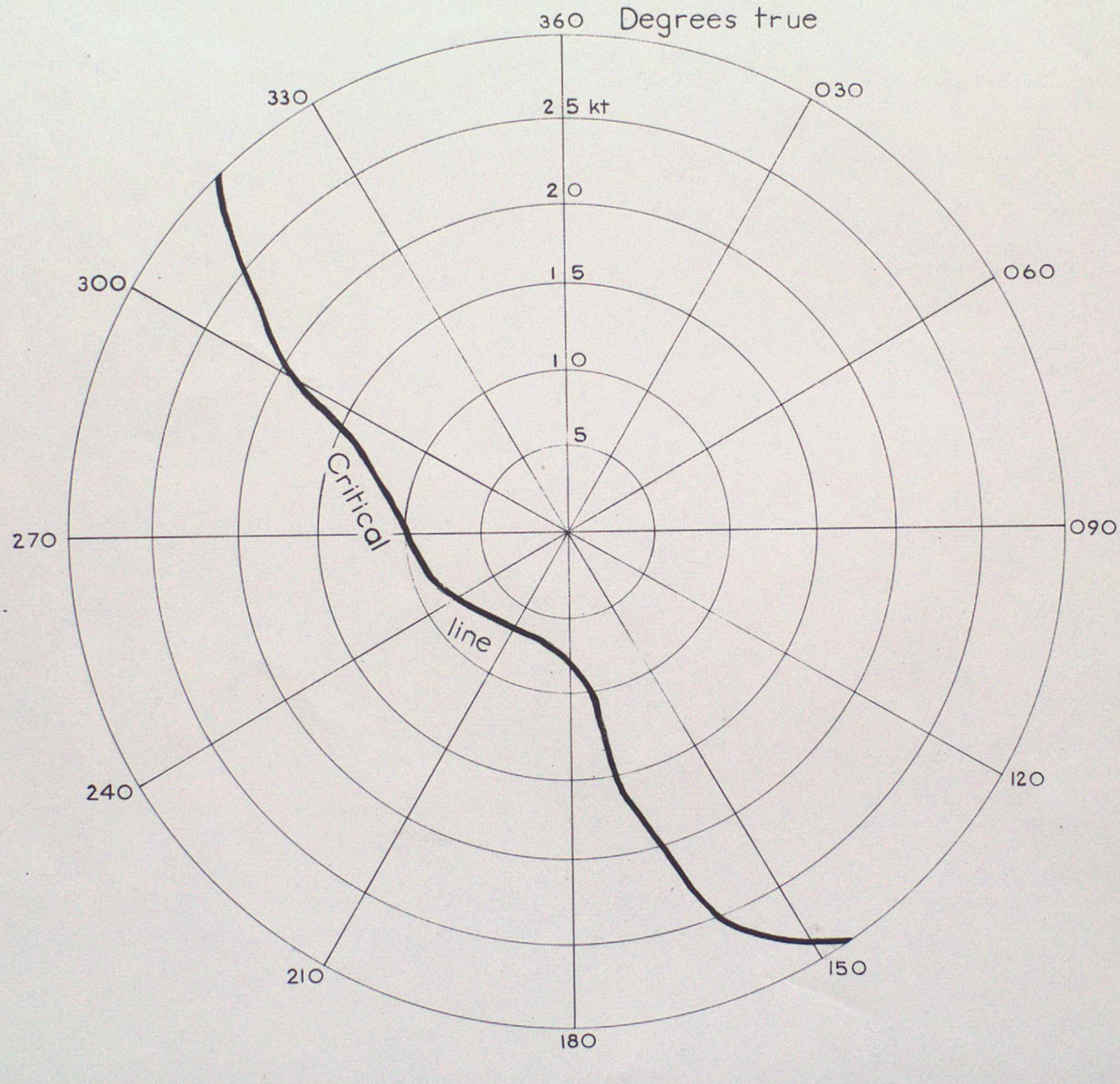


Figure I. If 0900 surface wind lies to SW of critical line sea breeze will not affect Scampton.

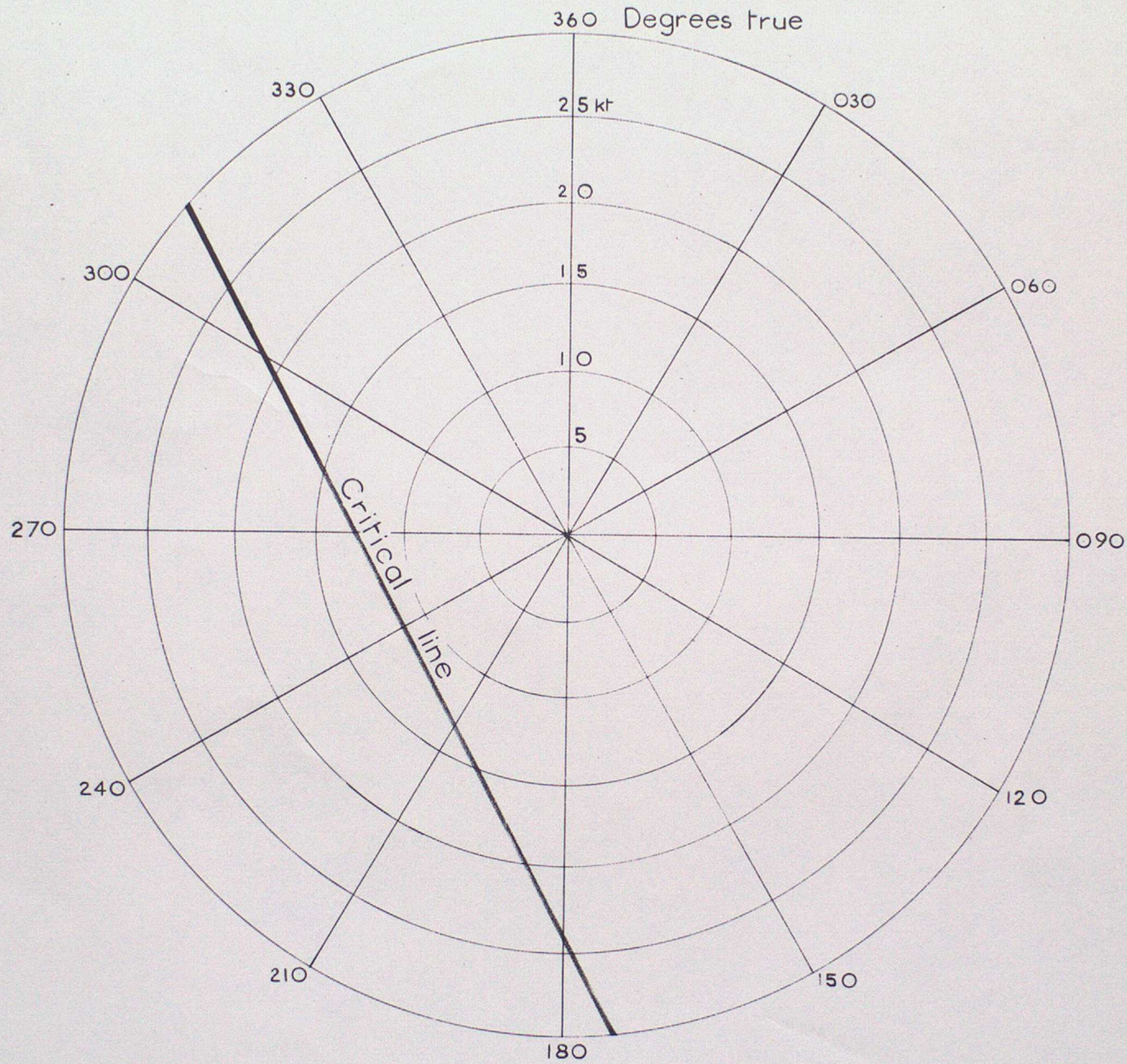


Figure 2. If 0300 gradient wind lies to SW of critical line sea breeze will not affect Scampton.

Comments on techniques for forecasting the sea breeze

by W.D.S. McCaffery

1. Introduction

A simple descriptive explanation of the basic mechanism of the sea breeze, including its penetration inland and the increasing seaward extent of its effects, has been given by Bleeker (1), (2). A mathematical model by Pearce (3), although neglecting the Coriolis terms in the equations of motion, enables a prediction graph for forecasting the sea breeze to be constructed similar to those of Watts (4) who relates the occurrence or non-occurrence of the sea breeze at Thorney Island to the strength of the (off-shore) gradient wind and the difference between air temperature over the land and the sea surface temperature.

The primary cause of the sea breeze is the differential rise in temperature of the land and sea surfaces during the day and the consequential temperature differences in the lower layers of the air over them. An important parameter in determining whether or not an observable sea breeze develops is the influence of the winds connected with the large-scale weather situation. A number of studies have concentrated on these two factors as being the two principal controls in the sea breeze mechanism. Other authors have considered the topography of the coast (Bleeker (2)) and the hinterland (Ref. (5)), introduced the effects of the Coriolis force (Haurwitz (6)), and discussed the importance of surface friction (Pearce (3) and Haurwitz (6)).

A brief discussion on the effect of the lapse rate is given in Ref. (5) but, as mentioned therein, this is difficult to treat theoretically. Pearce (3) found the effect of varying the stability in his mathematical model to be small giving little change in either the rate of inland penetration of the sea breeze or in the mean surface wind distribution. His model is restricted, however, to a stable atmosphere above the top of the sea breeze with a lapse rate from the surface to the level of the top of the sea breeze equal to or less than the dry adiabatic lapse rate. The complicating effects of condensation and the addition of latent heat through varying depths of the atmosphere are not considered.

Pearce concludes that a serious deficiency in the model is the suppression of the effect of stability over the sea (as well as the neglect of the Coriolis terms), but also states that the rate of penetration inland is determined mainly by the strength of the off-shore wind and the rate of heating of the surface layers. This may well be true when the heat input is spread upwards only to a limited extent by small-scale convection (dry thermals) in an initially stable environment. The situation is likely to be different, however, if convection is realised through a considerable depth of a conditionally unstable atmosphere. In this case the raising of the isobaric surfaces at moderate heights may be less than if the heat input were confined to lower

/levels

levels. On the other hand, with wet convection, released latent heat may play a significant part in the circulation, as suggested by Eddy (7).

The importance of convergence at a sea breeze front in promoting vigorous convection has been described by several authors (e.g. Findlater (8)), but the precise role of convection in the mechanism of the sea breeze and the sea breeze front has begun to receive attention only in recent years. This is largely because of the interest shown by glider pilots (Wallington (9)) who discovered that although the encroachment of sea air usually meant stability and loss of lift, sufficient lift to sustain soaring flight was often to be found in an extremely narrow belt at the sea breeze front. But the inland penetration of sea air and the behaviour of the sea breeze front bring many other meso-scale changes and after effects which are of general importance in detailed local forecasting.

2. Some characteristics of sea breezes

It is not the purpose of this section to describe or summarise known or suspected characteristics of sea breezes and sea breeze fronts, but to select and comment on some characteristics, and also on factors leading to the formation of sea breezes and sea breeze fronts, on which various authors are not in agreement and which may have a bearing on forecasting techniques.

Types of sea breeze

Several authors (e.g. Wexler (10), Defant (11)) recognise two types of sea breeze: a sea breeze of gradual growth on calm or light gradient-wind days and the frontal sea breeze on days with off-shore gradient-wind.

The sea breeze with little or no gradient-wind develops as a small circulation in the immediate vicinity of the shore. With continued heating of the land the circulation increases in horizontal and vertical extent and progresses landward and seaward. The horizontal extent of this "sea breeze of the first kind" (Defant) is not further discussed nor are the effects of varying degrees of stability mentioned.

With an off-shore component to the gradient-wind a "second kind" of sea breeze develops. The development takes place out at sea as described by Koschmieder (12) and a sea breeze front is formed which later crosses the coast and moves inland. The formation of the front at sea has been confirmed by several authors and recently by Angell and Pack (13) using transponder equipped tetroons ballasted to float at 500 ft. It should be noted that although, as previously mentioned, differential heating and the magnitude of the off-shore component of gradient-wind have generally been regarded as the principal factors in the sea breeze mechanism, Koschmieder's (12) model requires instability over land, and consequent convection, to upset the equilibrium between balanced forces holding the front out at sea and thus allow it to move towards and over the coast.

/Several

Several authors have considered the sea breeze circulation with on-shore gradient-winds. Conclusions vary from "the sea breeze component is then extremely weak" (Wexler (10)) to a statement by Eddy (7) "that, contrary to previous hypothesis, the land and sea breeze effect across the Texan coast is not always overshadowed by the normal on-shore flow around the Bermuda high." Other authors have described sea breeze fronts which, because of an on-shore gradient-wind component, have moved inland earlier in the day than is usual or have penetrated unusually far inland (Marshall (14)). It seems probable that noticeable sea breezes associated with on-shore winds will occur less frequently than with off-shore winds of suitable strength, but there is a need to determine factors which may result merely in an increase of surface wind, with slight changes of direction, as an increasing sea breeze component is added to an on-shore wind, and those which give rise to the development of more noticeable changes including the formation of a readily recognisable sea breeze front.

Effect of gradient wind

According to Wexler (10) an off-shore gradient-wind is more favourable for the development of sea breezes than gradient-winds parallel to the coast and Koschmieder (12) found that with gradient-winds parallel to the coast the rate of advance inland of the sea breeze at Danzig was negligible. This is in contrast to Wallington(9) who suggests a moderate or fresh conditionally unstable airstream blowing parallel to the coast as being favourable for the development of a sea breeze front (at least in southern England).

In considering the strength of the off-shore component, attention should also be paid to the actual direction of the gradient-wind. This was done by Watts (4) when constructing his scatter diagrams of land - sea temperature difference against 3000 ft wind. P.G. Wickham, an experienced glider pilot as well as weather forecaster, has suggested (private communication) that sea breeze fronts seem to form more readily, be better organised and move further inland when the pressure gradient is directed from sea to land rather than vice versa, i.e. for the south coast of England with winds from about west-north-west rather than north-east, an opinion also found in Ref. (5). The sea breeze (vertical) circulation may combine with a horizontal circulation which favours low level convergence at a sea breeze front and an additional factor which favours the development of the front is, according to Wickham and also Ref. (5), the formation of a suitably located heat low. The above, of course, is not to say that sea breeze fronts are not observed near the south coast with gradient-winds from north of east.

The strength of the off-shore component of the gradient-wind which will inhibit the onset of the sea breeze depends on the land - sea temperature contrast, probably on stability and the direction of the gradient-wind, and certainly on local topography. It is taken by most authors to be of the order of 10 to 15 kt, but Ref. (5) quotes gradient-winds of over 20 kt being required to neutralise the sea breeze at certain stations.

/Climatology

Climatology of sea breezes

A very short but useful note on the climatology of sea breezes and sea breeze fronts in Britain has been published by Wickham (15) who used a variety of published and unpublished data to construct, as well as the data allowed, a map showing the normal direction of the sea breeze and giving an indication of the average inland penetration of the sea breeze front by early afternoon, mid-afternoon and late afternoon. It is noticeable that sea breeze fronts are absent from Wickham's map in extreme south-west England, the mountainous hinterland of Wales, north-west England and Scotland except the south-east.

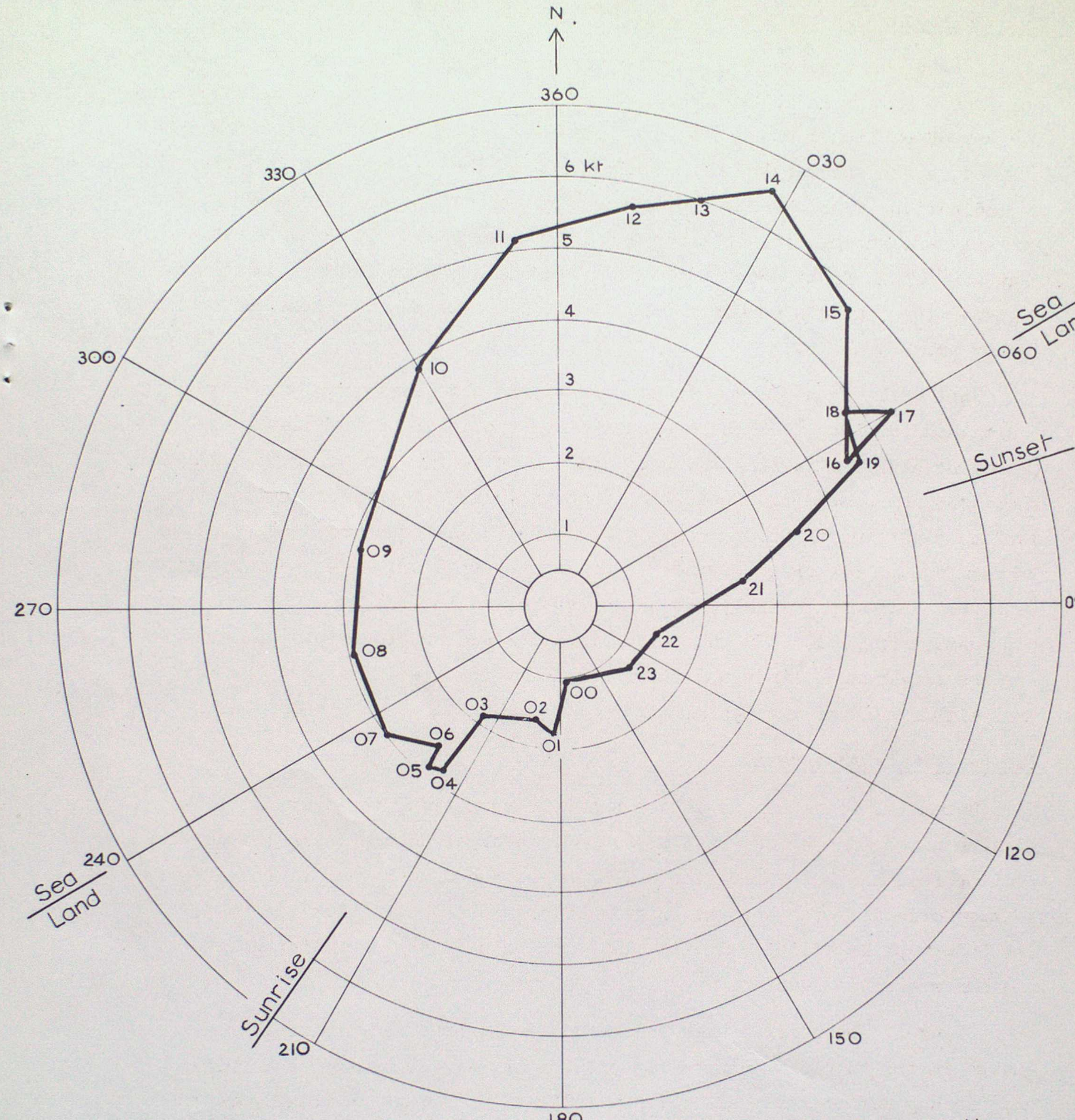
That well organised sea breeze fronts are not easily recognised in very mountainous regions is to be expected since the depth of the sea breeze (incoming sea air) is limited, but marked penetration can occur up valleys where the sea breeze combines with an anabatic flow to produce quite strong surface winds, up to about force 6 (Ref (5)). Although not indicated on Wickham's map, sea breeze fronts occur in eastern Scotland - see for instance Lamb (16) - though possibly not so marked nor so long as those of southern and eastern England. Wickham also discusses sea breeze fronts in Cornwall and the convergence lines sometimes formed by the meeting of sea breezes from either side of the peninsula.

The sea breeze hodograph

Normally, for a simple land - sea confirguration, the diurnal change in wind direction during a sea breeze - land breeze cycle is, in the northern hemisphere, a clockwise rotation which can be shown to be due to the effect of the Coriolis force and the inertia of the moving air (Haurwitz (6)). The hodograph is elliptical with its major axis in the direction of the maximum sea breeze vector.

Figure 1 shows, from data collected by the staff at Kinloss, the change in the hourly mean wind vectors for the station for 50 sea breeze days in May during the years 1958 to 1962. (Note that in the figure the mean wind vectors are directed inwards towards the centre as in a conventional synoptic station model plot. This does not alter the shape of the hodograph or its sense of rotation.) The approximation to an ellipse is reasonably well indicated and also the greater magnitude of the sea breeze as compared with the land breeze. The veer of wind during the day is not only observable in the mean, but is apparent on many, if not most, sea breeze days. Defant (17) remarks on the change of direction of the sea breeze during the day, but this is in contrast to several other authors who comment on the remarkable steadiness of the sea breeze. Indeed Wexler (10) suggests that the steadiness from a preferred direction is a factor in recognising the sea breeze. The Kinloss results for May show little change in direction for a period in late afternoon and early evening and it would be interesting to know if this

/characteristic



Note:- In this diagram the centre is taken as a station circle and the wind vectors are directed from the plotted point towards the centre.

Figure 1. Kinloss. Hourly mean wind vectors for sea breeze days in May 1958-62.

characteristic is repeated in other months of the year.

Friction and Topography

Local topography which departs appreciably from a reasonably long straight coast line and a fairly flat hinterland will be a major factor in controlling the diurnal variation of the sea breeze. Distance inland may also be important if only because well inland the sea breeze front, passing late in the day, allows little time for any variation in direction to become apparent before the breeze dies away.

Another feature which can be seen from Figure 1 is that in the mean, in May, the maximum sea breeze at Kinloss occurs about the time of maximum surface heating. If frictional effects are ignored the sea breeze, once established, should continue to increase in strength until the temperature difference between the land and sea air has increased to a maximum and then fallen to zero again. When friction is allowed for, a positive temperature difference between the land and sea air is required and, at coastal stations, the larger the coefficient of friction the nearer the time of maximum heating will the maximum sea breeze occur. Using values of the coefficient of friction determined from values over land, Haurwitz (6) found theoretically that the maximum sea breeze should occur about three hours after the time of maximum temperature difference between land and water. It is interesting to notice that at Kinloss, although the mean maximum sea breeze of 6.5 kt occurs in May at 1400 GMT when vector means, as used in the diagram, are calculated, the mean speed maximum of 9.5 kt occurs at 1600 GMT. In Ref. (5) it is stated that several stations report a maximum sea breeze about one hour after the time of maximum temperature.

Haurwitz (6) also demonstrated that the larger the coefficient of friction the more eccentric would be the hodograph ellipse. This is to say that when the maximum sea breeze occurs close to the time of maximum temperature difference between land and sea there should also be a relatively large change in speed as the direction of the sea breeze changes.

In discussing the movement inland of the sea breeze (Wexler (10)) states that hills and forests appear to obstruct the movement inland. Pearce (3), in his mathematical model, varied the depth of atmosphere affected by surface drag between five metres and 80 metres and this resulted in only slight changes in the distance penetrated. He concluded that the effect of surface friction is not a predominant one. It is interesting to note, however, that for the changes he considered the distance penetrated inland increased with increasing depth of the effects of surface friction.

The part played in the development of the sea breeze by low hills near the coast is likely to be complex. They offer a physical barrier to the flow but they also provide a heat source at a higher level than the

/immediate

immediate coastal strip. If, in addition, the ground slopes up from between east and south the heat received per unit surface area is greater than for a horizontal surface. Both these effects may induce an earlier and stronger sea breeze than would otherwise be the case. Movement of the sea air further inland may then depend on other factors as for instance Pepperdine's suggestion, in his note in this memorandum, of the part played by convection over the Lincolnshire Wolds in delaying the progress of the sea breeze front towards Scampton.

The effect of larger mountainous masses such as the Grampians has been commented on both by Goldie (18) and Lamb (16). In particular Lamb states that the stretch of the coast which lies nearest to the mountains is exceptionally liable to sea breeze and its effects. He also draws attention to the importance of the direction of the gradient-wind over the mountains since lee eddies are clockwise at the left-hand end of a mountain block (as seen from the direction of the main wind stream) and anticlockwise at the right-hand. For eastern Scotland this means that the circulation is anticlockwise with westerly, and clockwise with northerly gradient-winds. Such horizontal circulations restrict the coastal areas which are affected by the sea breeze and can also, at any one place, cause the sea breeze to set in from different directions and effect the diurnal change in direction of the sea breeze - see also Ref. (5).

Movement inland of the sea breeze front

The speed of movement inland of the sea breeze front is less than the sea breeze itself leading to convergence at the front and a narrow belt of upward motion of both the sea air and the displaced land air. Wallington (9) and others have described the "curtain-cloud" that sometimes forms in the moist rising sea air. Several authors agree on a mean speed of movement about half that of the sea breeze itself, a conclusion verified theoretically by Pearce (3) who calculated the rate of spread inland to be just over half the maximum surface velocity.

Pedgely (19) studying the sea breeze at Ismailia found the sea breeze front to advance inland during the afternoon at a rate which varies in a simple manner being slowest at the time of maximum temperature, a result also found by other workers in other parts of the world. After the time of maximum heating the front is observed to move inland at an increasing speed until finally all the momentum has been destroyed by friction.

The movement inland may also be complicated by surges or wave-like perturbations of the frontal surface. Simpson (20, 21) gives a distance of 10 or 15 miles between "bulges" in the sea breeze front and has described characteristic "bar-clouds" which often accompany them. The bulges are said to appear in the front on days with convection to 8,000 or 10,000 ft. Wallington (9) has also suggested that the front may decline in one belt while appearing to intensify in another belt a mile

/or

or so further inland. Theoretical studies by Ball (22) indicate that fluctuations might occur when the Coriolis terms are included in the equations of motion.

Mention has already been made of the effects of topography in promoting, for instance, the strong penetration up suitable valleys when a sea breeze is assisted by an anabatic effect. A less obvious effect can be noted in the tendency for sea air to flood south-westwards from the Wash area or south-eastwards from the estuaries of the Dee and the Mersey while to the north and south, the progress inland of sea breeze front appears to be retarded by hills which may be quite small.

As well as the effects of topography on the distance penetrated inland it is stated in Ref. (5) that for a distinguishable sea breeze to penetrate far inland the pressure gradient must be very slack. The distance also varies with the amount of insolation and is considered by some observers to be much influenced by the presence of a high lapse rate or of an inversion.

Depth of the sea breeze

The depth of the sea breeze is taken to be the depth of air flowing inland from a source over the sea. Sutcliffe (23) in a statistical study of the sea breeze at Felixstowe could find no evidence of a return current but other authors, e.g. Pedgley (19) and Findlater (24), present evidence of a returning current of sea air between the sea breeze flowing inland below, and land air displaced by the sea breeze front flowing seaward aloft.

Analysis of pilot balloon ascents on 94 good sea breeze days at Kinloss between 1958 and 1964 gave a mean depth of 1000 ft with a standard deviation of 600 ft and extremes of 200 and 2,800 ft. The observers at Kinloss found that sometimes the wind direction changed suddenly, while at others the direction changed gradually through a layer. In these latter cases the depth of the sea breeze was taken to be the level of the maximum change of direction with height. On six occasions sudden changes of wind direction with height were found at two levels. The lower heights were used in computing the results given above, but use of the upper levels does not significantly alter the results; the upper extreme was 3,200 ft.

In another study, at Tangmere, on 20 sea breeze days the mean depth of the sea breeze was 2,500 ft, the numbers of cases of depth of sea breeze occurring in various ranges being:

Table 1. Number of cases of depth of sea breeze

height range	500-1000 ft	1000-1500 ft	1500-2000 ft	2000-2500 ft	2500-3000 ft	3000-4000 ft	Total
	1	2	2	2	9	4	20

/Sutcliffe

Sutcliffe (23), in his study of the depth of the sea breeze at Felixstowe found a mean depth of 500 to 600 metres. This is more in accord with the mean depth(of about 1650 ft.) of 11 cases published by Peters (25) for Worthy Down, Winchester than with either the Kinloss or Tangmere results. Worthy Down is about 25 miles from the Solent and Spithead, Tangmere about five miles from the south coast, Kinloss about a mile and a half and Felixstowe less than one mile from the North Sea.

Wexler (10) states that there is considerable diurnal variation in the depth of the sea breeze with a maximum in the middle afternoon hours. The pilot-balloon ascents at Kinloss, which were done at various times as opportunity occurred in normal station daily routine, give the results shown in Table 2 (the figures in brackets in Tables 2 and 3 are calculated using the upper of two levels in wind discontinuity when these occurred):

Table 2. Variation in depth of sea breeze at Kinloss with time of day (GMT). See text for figures in brackets.

Time of day	Mean depth of sea breeze in ft.		Number of pilot-balloon ascents.
0700 - 0800	400		1
0800 - 0900	500		1
0900 - 1000	720		5
1000 - 1100	835		9
1100 - 1200	700		5
1200 - 1300	836	(859)	21
1300 - 1400	1,184	(1,308)	19
1400 - 1500	877	(1,139)	12
1500 - 1600	990	(1,080)	10
1600 - 1700	1,575	(1,950)	4
1700 - 1800	1,400		4
1800 - 1900	1,933		3
			94 Total

There is some evidence in the table for an increase in the depth of the sea breeze with time until during the afternoon, but thereafter results are inconclusive. Wexler, however, also states that the sea breeze fluctuates in depth, the fluctuations being mirrored in changes in surface wind velocity and also occasionally in temperature and humidity. Statistically the fluctuations should be averaged out, but there are clearly too few observations at either end of Table 2 to support firm conclusions.

The Kinloss results were also analysed to see variations in the depth of the sea breeze with the length of time after the sea breeze had set in. The results are given in Table 3 which indicates an increasing depth during

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the first seven hours or so but with too few observations after this time to allow conclusions to be drawn.

Table 3. Variation in depth of sea breeze at Kinloss with time after onset. See text for figures in brackets.

Time in hours after onset	Mean depth of sea breeze in ft.	Number of pilot-balloon ascents
0 - 1	585	17
1 - 2	857	14
2 - 3	917 (950)	15
3 - 4	1,011	14
4 - 5	1,086	8
5 - 6	1,240 (1,690)	10
6 - 7	1,478 (1,856)	9
7 - 8	2,800	1
8 - 9	1,100	1
9 - 10	3,800	2
		91 Total

In the above tables all occurrences of sea breeze have been considered together, but the depth of the sea breeze is likely to vary with varying synoptic conditions. In Ref. (5) for instance it is stated with respect to Thorney Island that the depth of the sea breeze is shallow (500 ft) when there is a marked anticyclonic inversion at 2000 to 3000 ft, and deep when large cumulus clouds are developing inland.

In descriptive accounts of the sea breeze front over southern England, e.g. Wallington (9, 26) and Simpson (20), the base of cumulus forming in the land air is about 4000 to 5000 ft with "curtain-cloud" and "bar-cloud" forming at a much lower level. The nose of the front, outlined by "curtain-cloud" or often by haze may be nearly vertical, but two or three miles nearer the sea the slope has been measured to be about one in 100 (Simpson (20)). Peters (25) in his study of the sea breezes at Worthy Down, found from pilot-balloon observations that the sea air occasionally arrives overhead in advance of the sea breeze at the surface, a fact also noted by Angell and Pack (13) in their tetroon experiments. Defant (17) writes "this breeze often sets in with considerable gustiness, sometimes in the form of a protrusion similar to a cold front".

Stability

Some comments on the role of stability or instability have already been given in the introduction. Further comments are made below.

Since the basic sea breeze mechanism maintains a circulation, though

/not

not necessarily a closed one, in which there is rising air over land and descending air over the sea, stability of the sea air and a degree of instability in the land air should assist the circulation. What there seems little agreement on is the degree of instability of the land air most favourable for the onset of a well developed sea breeze, the formation of a marked sea breeze front and its penetration well inland. This is possibly because the effects of local topography and perhaps other synoptic parameters combine to require rather different stability criteria in different areas.

Some of the effects of instability may act in opposite directions as is commented on in Ref. (5) in discussing sea breezes in the Montrose area. Here convection over the mountains favours the development of a draught of air from the sea to make good the loss from the surface inland. But on some days of westerly winds, when a sea breeze might be expected to appear later, convection has the effect of strengthening the westerly wind at the surface throughout the middle of the day. The writer concludes in this section that "perhaps intermediate lapse rates are most favourable for sea breeze" though in another section, commenting on sea breezes generally, he writes: "In stagnant air the vigorous convection is generally well inland, with fine weather in the sea breeze zone itself; in these conditions the sea breeze may extend further than when convection does not extend so high."

Again in Ref. (5) it is stated that under an inversion, because of the damping of turbulence, the sea breeze flows in freely, but in discussing station reports several examples are given of localities where the presence of a marked inversion appears to inhibit the onset of the sea breeze. Wexler (10) states that the stability of the land air is a factor in determining the time of onset of the sea breeze, the most favourable time for the penetration inland of the sea breeze is at the time of the greatest diurnal instability i.e. during the early afternoon. It is not clear if by "the most favourable time for the penetration inland of the sea breeze" Wexler means the time of crossing the coast or the time of maximum rate of penetration inland. Neither of these interpretations is in accord with Pedgley's (19, 27) conclusion that the rate of movement of the front is slowest at about the time of maximum temperature. In a radar study of a sea breeze front Eastwood and Rider (28) observed that the front, first in evidence near the coast at Felixstowe at 1200 hr, accelerated gradually until sunset by which time it was moving at 6 kt.

Wexler (10) also states that if the land air remains stable the sea breeze front, forming out at sea, may never reach the shore, but also points out that if, during the afternoon, the gradient-wind decreases the sea breeze may often penetrate to the shore even though the land air remains stable.

Watts (4), in his study of sea breezes at Thorney Island, remarks that

/the

the sea breeze at near-coastal stations sets in suddenly if inland convection is fairly deep, but only gradually if convection is shallow. The two illustrations indicate convection to be to about 8000 ft in one case and 4000 ft in the other.

While a degree of instability, whether or not occurring under an inversion, may aid in the development of sea breezes, moderate or vigorous convection producing well developed cumulus clouds is not necessary for the development and inland penetration of sea breezes at least in certain areas. Of the 58 cases of sea breezes reaching Worthy Down discussed by Peters (25), half occurred on days of cloudless or almost cloudless skies. The sea breeze front observed by radar by Eastwood and Rider (28) occurred in quiet anticyclonic conditions with little wind and almost cloudless skies. It was detectable because of the variation in the refractive index of the air, and possibly the presence of birds feeding in the up-draught, and was later confirmed by examination of the meteorological records at several stations. The front penetrated a maximum distance of 50 miles from the coast and stretched in a (broken) arc from East Anglia to Kent; another branch, presumably moving in from the south coast, existed over Sussex to make a total length a little short of 120 miles.

For purposes of forecasting, it may be profitable to study two types of sea breeze. There are those occurring in quiet anticyclonic conditions when skies may remain almost cloudless and the sea breeze, although possibly moving inland on a broad front, brings changes to wind, temperature, humidity and possibly to visibility and pollution. There are also those occurring in conditions favourable to the formation of sea breeze fronts characterised by marked changes in cloud on either side of the front and/or the significant development of cloud and possible showers or thunderstorms at the sea breeze front itself, as well as by changes in wind and temperature etc. Clearly, in the latter case, there must be sufficient instability assisted by convergence at the front to produce marked cloud development and possibly precipitation. The effects, if any, of such development on the movement of the front inland must be considered as well as the influence of the broad-scale synoptic pattern and the local topography.

Further information on sea breezes

A very full bibliography on sea breezes varying from Plutarch upto 1963 is given by Baralt and Brown (29).

3. Forecasting Techniques

The three articles on sea breeze forecasting techniques included in this memorandum all consider some aspect of convection in attempting to forecast the inland penetration of the sea breeze. This is in contrast to the approach of Watts (4) in his discussion of the sea breeze at Thorney Island. Watts acknowledges that the degree of instability has an effect on the way the sea breeze may develop, but does not require any measure of

/instability

instability as a necessary condition.

A technique developed at Chivenor (Ref. 30) for forecasting whether or not a sea breeze will occur also depends only on a temperature difference between land and sea and a wind criterion regardless of the degree of stability. A sea breeze is forecast at Chivenor if:

$$T_x \geqslant T_s + 1 \cdot 8V + 4$$

where

T_x = forecast inland maximum temperature in degrees F (assuming no modification by sea breeze)

T_s = sea temperature in degrees F at St Govan Light Vessel

V = component from 110° of geostrophic wind in knots (offshore component).

Although the meteorological office at Thorney Island is described by Watts (4) as being three miles from the open sea, the water of Chichester harbour must have a modifying influence and the effective distance of the station from the sea is probably much less. Chivenor also is three miles from the open sea, but the tidal estuary of the River Taw and its numerous tributaries should make the effective distance rather less. At these near-coastal stations some success is therefore claimed in forecasting sea breezes without considering a stability parameter. Since, however, at coastal stations, where for very local forecasting the problem of inland penetration is perhaps of secondary importance, a reasonable degree of success in forecasting sea breezes may well be achieved by considering two major factors which may determine whether or not a sea breeze is to be expected at all.

The technique described in Article 1, attempts to forecast the arrival of the sea breeze front at Winchester and Lasham on days "when soaring was possible at Lasham". This requirement at once focuses attention on sea breeze fronts forming and moving inland on convective days, though without necessarily excluding cases when cloud amounts are very small or indeed absent altogether. The conclusion that the drier the lower layers of the atmosphere (low surface relative humidity) the further inland the front is likely to penetrate is in accord with the case on 20th June 1960 described by Eastwood and Rider (28) when with a dry atmosphere the cloudless sea breeze front penetrated 50 miles inland. At midday, at Crawley, a near-isothermal layer extended from 925 mb and with maximum surface temperatures about 25°C, dry thermals probably extended to about 4000 ft.

The suggestion that dryness is a factor in aiding the inland penetration of the sea breeze is not sustained in Articles 2 and 3 where, indeed, the emphasis is on the presence of cumulus cloud providing visible evidence of convection. Released latent heat of condensation may play an important

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part in assisting vertical motion inland on some, possibly many, occasions but it seems unlikely that it should always be a necessary condition for the movement inland of sea breezes from the east coast of England, especially to Manby only six miles from the sea. It seems more likely that convection, which on some scale may be a necessary requirement, occurs in an atmosphere which is usually moist enough to produce clouds and hence the convection is indicated in this way. This is to say that at Manby on most occasions when conditions are suitable for the sea breeze to occur they are also suitable for the development of cumulus cloud. Other occasions when conditions favour a sea breeze at Manby are likely to occur but may do so only rarely.

Differences in the synoptic climatologies of the south coast and the east coast, together perhaps with differences in topography may thus help to explain why both at Scampton and Manby visible evidence of convection is looked for while at Lasham, although convection is required, a suitably dry atmosphere and a high cloud base is regarded as a favourable condition. Low relative humidities are likely to be associated with small amounts of cloud, allowing maximum surface heating, or with cumulus developing later in the day only after high surface temperatures have been reached. Since the distance penetrated inland depends, in part, on the magnitude of the differential heating there may therefore be a relationship between this distance and relative humidity. Again the Scampton requirement that convection should be limited to below 12,000 ft may reflect a possible relationship between depth of convection and total cloud amount. A rule of thumb developed at Tangmere, about five miles inland from the south coast, is that on days when the sea breeze might otherwise be expected the coastal strip does not clear of cloud if instability extends above 8,000 ft. (P.D. Borrett, private communication). A similar rule for Leconfield, 12 miles inland from the Yorkshire coast, requires a good check to convection at about 6000 ft before the sea breeze can be expected to arrive though this does not exclude the possibility that the sea breeze may make some progress inland. The other requirements for a sea breeze to reach Leconfield are: air temperature rising to $6^{\circ}C$ or more above sea temperature at the Humber Light Vessel and offshore component of geostrophic wind not in excess of 7 kt (Ref. 30). Manby and Leconfield, both situated in a coastal plain to seaward of the Wolds, would appear to differ significantly only in their distance from the North Sea. Yet at Manby a requirement is for convection to extend to above 5,000 feet while at Leconfield convection has to be checked at 6000 ft. These conditions hardly seem to be compatible. Scampton and Lasham, though both about 25 miles from the sea, are clearly less comparable with each other than are Manby and Leconfield. Some differences in the criteria for a sea breeze to reach the station are therefore likely and it may be possible to reconcile the requirement at Scampton for cloud tops to be below 12,000 ft with the condition at Lasham for cloud base to be above

/5,000

5,000 ft. A common requirement for forecasting at least certain types of sea breezes seems to be for a degree of instability, and possibly both height of cloud base and top should be considered as well as total cloud amount and time of day convection begins to be in evidence. It would in any case be desirable to record the depth of inland convection since several authors, e.g. Ref. 5, state that the distance penetrated inland is greater with more vigorous convection, but without defining "vigorous convection". Convection which is too vigorous seems to inhibit the formation and/or the spread inland of the sea breeze, at least at certain places in certain conditions.

As a separate requirement to deal with cases of sea breezes when cloud does not develop, or is not much in evidence, the formation of dry thermals should be considered further. In article 3 it is stated that there were some cases of failure of the rules for forecasting the sea breeze when dry convection occurred before 0900 GMT, but was not logged because of the absence of cloud. Since thermal turbulence on some scale will occur on any fine morning, a parameter defining the magnitude of dry convection is probably required. From the radio-sonde plot at Figure 4 of Article 2, and allowing for maximum temperatures of about 22°C reached on that day, dry convection to about 3,000 ft could be expected eventually. That sea breezes were not in evidence is more likely to be due to other reasons than dryness alone. The marked inversion at Aughton at midnight, if representative of air later arriving over Lincolnshire may be significant in inhibiting, for some time, convection through any appreciable depth of the atmosphere.

Technique due to Pearce (3)

With some assumptions, Pearce's mathematical model yields three simple relationships from which can be determined whether or not a sea breeze will occur, the mean strength of the sea breeze (strictly the component normal to the shore line) and the distance penetrated inland.

A sea breeze will occur and penetrate inland on any day when

$$Q \geqslant C_1 U^2$$

where Q is a parameter which is a measure of the heating inland and is described more fully below, C_1 is a constant and U is the minimum offshore wind component. If Q_{max}, corresponding to the total inland heating, is less than $C_1 U^2$ there will be no sea breeze. If the inland heating is such that Q equals or exceeds $C_1 U^2$ then a sea breeze will start to move inland at a time when Q reaches this value.

The mean strength of the sea breeze, u_m, (mean over the distance inland from the shore) after a time T has elapsed since heating began is given by:

$$u_m = C_2 Q^{\frac{1}{2}}$$

/where

where C_2 is another constant and Q is a measure of the inland heating after time T.

The distance penetrated inland, X, is given by:

$$X = C_3 T Q^{\frac{1}{2}}$$

where C_3 is a third constant. The maximum distance penetrated inland is given by the product of Q_{max} (total inland heating) and the time elapsed since heating began. This can probably be taken simply as from sunrise to time of maximum temperature.

Pearce computes values for the constants in his equations but goes on to point out that the formulae should be used mainly as guides to the kind of relationships to be sought in predicting sea breezes for a given locality and the constants determined empirically.

<u>Determination of Q</u>

Pearce defines a parameter H, which is approximately equal to the increase of potential energy per unit mass of inland air due to heating, by the identity:

$$H \equiv gh\bar{\theta}_i'/\theta_o$$

where

- g is the acceleration due to gravity
- h is the upper limit of integration for the sea breeze and may be taken as the top of the convection layer well inland
- $\bar{\theta}_i'$ is the mean value, up to height h, of the increase of potential temperature well inland
- θ_o is the initial potential temperature.

Since g may be regarded as a constant and since θ_o (in degrees Kelvin) will vary only by about 10% we may take θ_o as constant to a first approximation and write:

$$H = Kh\bar{\theta}_i' = KQ$$

where K is a constant.

In the form of the equations given in the section above, the parameter H appearing in the originalrelationships has been replaced by Q ($= h\bar{\theta}_i'$) and a new constant introduced. Q is determined from the tephigram as follows.

Using a suitable early morning ascent construct a modified environment curve by drawing a dry adiabatic to enclose between it, the original environment curve and the surface pressure curve an area on the tephigram equivalent to the available "Gold squares" for the time of year. The depth of the convective layer, h, is then given by the depth of the dry adiabatic layer from the surface. Since the change in potential temperature at the top of this layer is zero, the mean value of the increase of potential temperature, $\bar{\theta}_i'$, is taken to be half the difference between the potential

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temperatures at the surface of the modified and the unmodified environment curve. The product of h and $\bar{\theta}'_i$ so determined then gives Q_{max}. The units are not important since conversion factors and dimensions may be regarded as being contained in the constants to be determined empirically. A similar construction using, for instance, the method of Johnston (31) and tables from the Pocketbook for Forecasters enables Q for earlier times of the day to be obtained and the time of onset of the sea breeze forecast.

The above method of determining Q applies strictly when cloud does not develop, but similar relationships may exist when cloud does develop. $\bar{\theta}'_i$ can be determined as before, regarding the air as dry (see Jefferson (32)) and making some allowance for the effectiveness of the cloud in reducing the temperature rise. The determination of h may prove more difficult; the parcel or slice methods of finding the upper limit of convection may be an overestimate for what may be regarded as the mean depth of air through which the heat input is distributed. On the other hand to determine h as if the air were dry is to ignore any effects of latent heat. Some compromise may therefore have to be sought empirically.

An investigation into the sea breeze at Thorney Island is currently being made by E.H.C. Donophy (private communication). Among other things, Pearce's suggestion of using areas on the tephigram as a measure of the heat input is being tried. Energy changes up to the time of onset of the sea breeze are determined from the area bounded by a dry adiabat through the surface temperature at this time, the surface isobar and a suitable upper air environment curve modified firstly to the station's minimum temperature and secondly to the sea temperature from the nearest reporting station. Two scatter diagrams are being constructed using energy as determined by these two methods as abscissae; in each case the ordinate is the offshore wind component.

4. Further work

In forecasting the onset of a sea breeze at a coastal station some success has already been achieved by considering only two main parameters - the strength of the offshore wind component and a parameter representative of the surface heating. A refinement is to allow for the actual direction of the wind, while the technique suggested by Pearce takes some account of the depth through which surface heating may be spread. It should therefore be worthwhile attempting to develop this method especially for places with a long straight coast line and a fairly flat hinterland. For other localities the technique might still prove worthwhile, since topographic effects and possibly other effects arising, for instance, out of the synoptic climatology of the area, might be accounted for in some measure in the empirical determination of the constants.

Mostly the sea breeze is considered when winds are otherwise very

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light or have an offshore component less than a limiting value. There is some evidence, however, that with onshore winds the sea breeze occasionally organises itself to form a sea breeze front with discernible properties. Further evidence of this and the circumstances in which it may occur should be sought.

At both inland and coastal stations the sea breeze is said sometimes to set in suddenly and sometimes gradually, with or without gustiness. Watts (4) suggests that this is related to the depth of convection. It must also be indicative of the sharpness of the sea breeze front and its speed of movement. Criteria are needed for distinguishing between non-frontal and frontal types of sea breeze especially at the coast and for distinguishing, especially inland, between fronts which may be almost cloudless and those which are marked by cloud and possibly precipitation. The role of convection in these various manifestations of the sea breeze needs investigating, particularly the depth of inland convection in its relation to the formation and movement of well-marked sea breeze fronts. The properties of the sea breeze, changes of speed, direction, squalls and gustiness, for example, need further study in relation to its various types.

Conflicting statements on the movement of the sea breeze front inland have already been noted. Clearly more detailed information on how the front moves under various circumstances and in different areas is required; also needed are observations of any wave-like structure or of movement in surges.

None of the methods reviewed make any allowances for changes in sea temperatures. Where reasonably deep water persists at all states of the tide not much change of temperature will occur, but in some places where large areas of shallow water remain or mud flats are exposed at low water some allowance for the state of the tide may be necessary. The major difficulty seems to be in accumulating for comparative purposes a sufficient number of cases which are reasonably similar synoptically and differ mainly in the state of the tide.

An aspect of the sea breeze which has received little attention, but which may be of some interest to yachtsmen, is the changes which go on over the sea as a result of the land breeze - sea breeze cycle. Changes in cloud type and amount and occasionally in showeriness occur as stability increases over a widening belt of coastal water. Also conditions of little wind or light offshore winds give way to a moderate or even fresh breeze towards the shore. A more exact knowledge of the nature of these changes and the width of the belt affected is required.

As well as attempting to find and use empirical rules for forecasting the sea breeze, forecasters should try to locate and follow sea breeze

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fronts on charts of hourly observations. This is possible on at least some occasions and a few forecasters, working frequently with glider pilots, have with practice, and through familiarity with meso-synoptic models of the sea breeze front, begun to develop an expertise. Small indications from wind, temperature, humidity and cloud, and possibly from visibility and precipitation, may be boldly used in analysing charts preferably on a scale of one in two million or even one in one million. The wind field is best studied by means of surface streamlines. Sometimes a pressure analysis with one-mb or even half-mb isobars is helpful in indicating, for instance, the development of heat lows inland.

Well marked sea breeze fronts with precipitation should be detectable by radar; detection of dry fronts depends on the characteristics of the radar, but some assistance in mapping sea breeze fronts should be given by the radar on at least some occasions.

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