M.O. 524k

AIR MINISTRY

METEOROLOGICAL OFFICE

PROFESSIONAL NOTES NO. 111

(*Eleventh Number of Volume VII*)

NOCTURNAL WINDS

By E. N. LAWRENCE, B.Sc.

LONDON

HER MAJESTY'S STATIONERY OFFICE

1954

Decimal Index
551·553·11 : 551·555·4

ONE SHILLING NET

Prof. Notes Met. Off.,
London, 7, No. 111, 1954

NOCTURNAL WINDS

By E. N. LAWRENCE, B.Sc.

Summary.—The relationship of katabatic winds and land-breezes to topography, soil and ground cover is examined, and the speed, depth, frequency, temperature, conditions of flow and other characteristics of these winds are discussed in the light of results of the present investigation and in relation to the results of other surveys and experiments. An empirical formula for the speed of the katabatic wind in terms of the angle of slope and distance from the sea is obtained for extensive flat slopes. The magnitude of the land-breeze (and hence the nocturnal wind) over England is assessed.

Introduction.—For the prevention of damage by frost in orchards it is important to have some idea of the winds associated with " radiation frosts ". A forecast of the wind is particularly helpful in the use of fine water-sprinkling devices or similar anti-frost equipment and in smoke-screen methods, all of which depend for their success on the correct placing of apparatus. On many sites, owing to local topography, the wind is often very variable, and in some instances it may be difficut to arrange for the necessary protection from frost by means of screening or spraying. But there are many cases where a knowledge of the local nocturnal winds would help considerably towards success in alleviating frost risks, either by means of site selection or by the use of anti-frost equipment.

In this investigation the following definitions are used :—

Land-breeze.—When the land and sea are cooled by radiation, the air over the land tends to cool more rapidly than the air over the sea, and the colder, denser, land air tends to flow towards the sea. This flow is called a land-breeze.

Katabatic wind.—When the air on sloping ground is cooled by radiation (as on a generally calm, cloudless night) it tends to flow downhill. This flow is called a katabatic wind.

Nocturnal wind.—This term is applied to the wind which results from a combination of katabatic wind and land-breeze. Thus a nocturnal wind can be said to have a katabatic-wind component and a land-breeze component.

Data used.—The area of investigation covered most of England and the sites referred to were mainly within the British Isles. Any site for which there were night observations of wind was considered. Use was made of pressure-tube anemograms where possible, but the data from stations making three-hourly observations were used. In special cases, records from a station making only one night observation daily were examined. Data of wind speed in terms of miles per hour or knots were essential, but use was made also of observations in Beaufort force. The data used in this investigation were obtained mainly from the following stations (see Fig. 1) :—

Abingdon	Flash	Mildenhall
Ashbourne	Fleetwood	Shawbury
Birmingham (Edgbaston)	Gorleston	Shobdon
Birmingham (Elmdon)	Harwarden	Shoeburyness
Calshot	Liverpool (Bidston)	South Farnborough
Cardington	Liverpool (Speke)	South Shields
Cranwell	Lympne	Southport
Croydon	Madley	Spurn Head
Driffield	Manchester (Barton)	Stonyhurst
Dunstable	Manchester (Ringway)	Tangmere
Felixstowe	Manston	Wethersfield

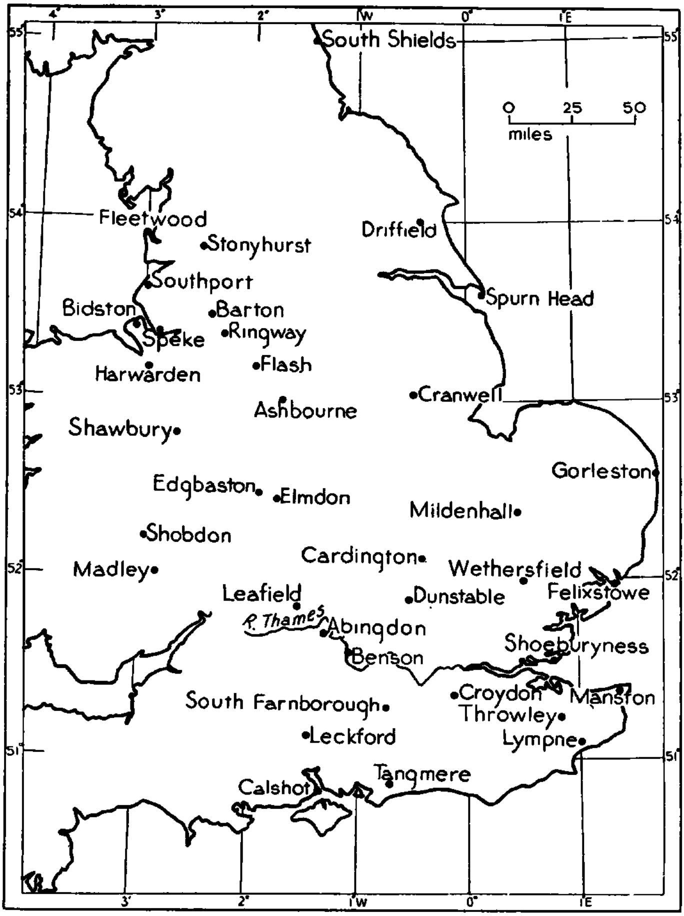


FIG. 1—STATIONS USED IN THE INVESTIGATION

Sixteen of these sites were used as " slope " sites (see below) and for most of these, from 30 to 100 or more occasions were selected foı examination. Most of the remaining sites were used in the construction of the land-breeze chart.

The data covered mainly the period 1941–52 and the investigation dealt primarily with the spring months of March, April and May. Occasionally where data were scarce, observations in other months were considered.

The wind observations used refer to the surface wind, the standard height for which is 33 ft. (10m.). In practice, the effective height was mainly within 15 ft. of this value.

Method of investigation.—Meteorological sites were classified as follows :—

(*a*) Sites in flat country, i.e. flat for at least several miles around the site, which on calm nights do not appear to receive any cold-air drainage from high ground in the neighbourhood.

(*b*) Sites on broad flat slopes (" slope " sites), excluding, as far as possible, sites near hill tops, on valley floors, or on banks of narrow valleys.

(*c*) Sites of more irregular topography which could not be included in types (*a*) and (*b*).

The *Daily Weather Report* was used as an aid for selecting occasions for examination, namely those when the pressure was fairly uniform over a considerable area around the site (i.e. when little or no geostrophic wind existed) and when the sky was cloudless or covered with only small amounts of cloud or when the cloud was in the form of cirrus or very thin upper layers. Where possible, only those days were used when the difference between the minimum screen temperature and the minimum ground temperature was at least 6°F.

Land-breezes.—The first stage of the investigation was the assessment, in respect of category (*a*) sites, of the magnitude (*L*) and the direction of the land-breeze for different locations. For a straightforward estimation of the land-breeze it is necessary to have a clear night preceded by a day with light winds which show a marked change of direction around dusk, assume a fairly steady land-to-sea direction during the night, and are followed by a further marked discontinuity of direction around dawn. If the light day-gradient (surface) wind is in the same direction as the land-breeze, the excess of the night wind over the early-evening wind would appear to give a good estimate of the land-breeze. On the other hand, when the gradient direction differs from that of the land-breeze and it would appear that a very light gradient wind would persist at the surface, a good estimate of the magnitude of the land-breeze may be obtained by subtracting a computed value of this gradient wind from the observed night wind, using the triangle of velocities.

As might be expected, it was found that the values of the magnitude of the land-breeze for a particular site varied according to the " strength " of the radiation night, i.e. according to the rate of outgoing radiation. Using either the average value, where several values (within a small range) were obtained for apparently ideal radiation conditions, or the maximum value, the assessment of the magnitude of the land-breeze at different places for March, April and May was plotted on a chart in the form of isopleths at intervals of 1 m.p.h. (see Fig. 2). The directions were not plotted, as these were generally from land to sea and roughly at right angles to the isopleths, but where the latter " wavered " for small sea inlets, the general direction was found to be outward from the centre of the land mass. The latter result is in accordance with that obtained by Hawke[1*], who found that for the Lancashire region the prevailing wind during the winter was south-easterly and not the general prevailing south-westerly wind direction.

Katabatic winds.—The second stage of the investigation was the assessment, in respect of category (*b*) sites, of the magnitude (*K*) and direction of the katabatic wind at different places.

It was found that on quiet radiation nights, at sites well inland, the wind came from the direction of high ground in the neighbourhood. Such a down-slope direction of the wind was, in fact, a useful indication that conditions were suitable for the assessment of the katabatic wind. This rule of wind direction applied only to inland sites within category (*b*). The winds observed at category (*b*) sites generally could be regarded as nocturnal winds resulting from a combination of katabatic wind and land-breeze (when present). The magnitude (*V*) of the nocturnal wind was assessed as in the case of *L*, estimates on nights of light gradient (surface) winds being obtained as before. Where the direction of slope and the direction towards the sea differed, i.e. the nocturnal wind was not directly down slope, it was considered to be the resultant of a land-breeze and a down-slope wind. Using the latter principle, the component due to the land-breeze, as interpolated from Fig. 2, was subtracted from the nocturnal wind to obtain the katabatic wind component.

---

* The index numbers refer to the bibliography on p. 13.

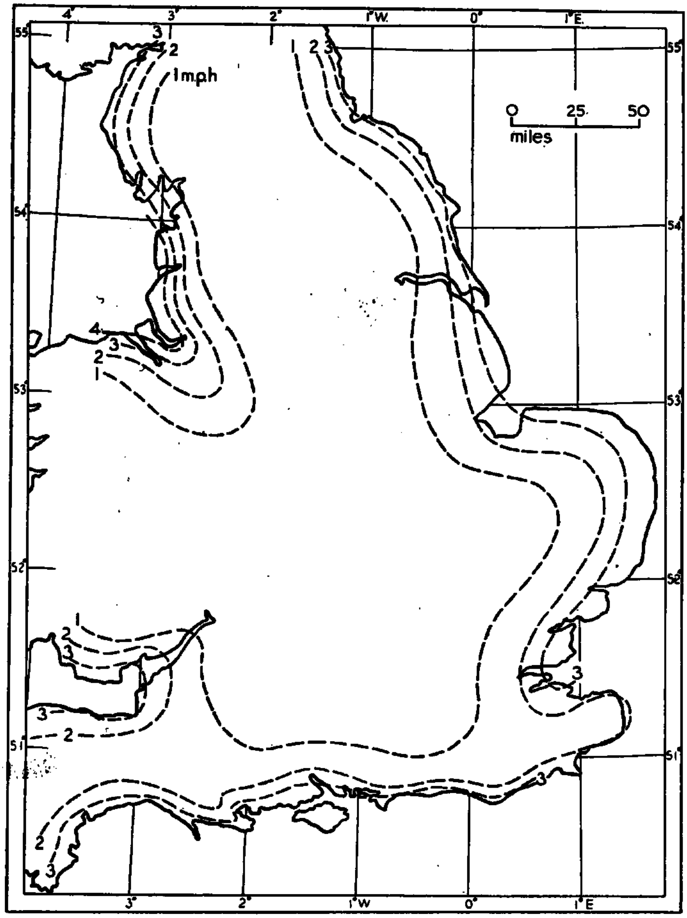


FIG. 2—LINES OF EQUAL MAGNITUDE OF LAND-BREEZE MARCH–APRIL–MAY

Discussion of results.—In connexion with diurnal winds in mountainous districts, Jeffreys[2] states that " it looks probable that the slope of the mountain will have an important influence on the motion of the air." Investigations by Heywood[3] confirmed this, and Brunt[4] states that " Heywood's discussion makes it clear that the katabatic flow starts in the upper valley, where the slope is steepest." Furthermore, as the katabatic wind is caused by the drainage of cold air due to cooling by radiation of the earth's surface, it can be expected that the strength of the katabatic wind is closely related to the net rate of outgoing radiation and also that the katabatic wind at a given site will be closely linked to the distance of that site from the sea. The maximum magnitude of the katabatic-wind component was therefore plotted against distance (x miles) from the sea of the centre of the area supplying cold air to the site, the so-called " donor area "[5]. When smoothed, the resulting curves (see Fig. 3) satisfy the following formula :—

$$K^2 = \frac{2x}{1{\cdot}4 + 100 \tan \theta}$$

where θ is the angle of slope of the ground.

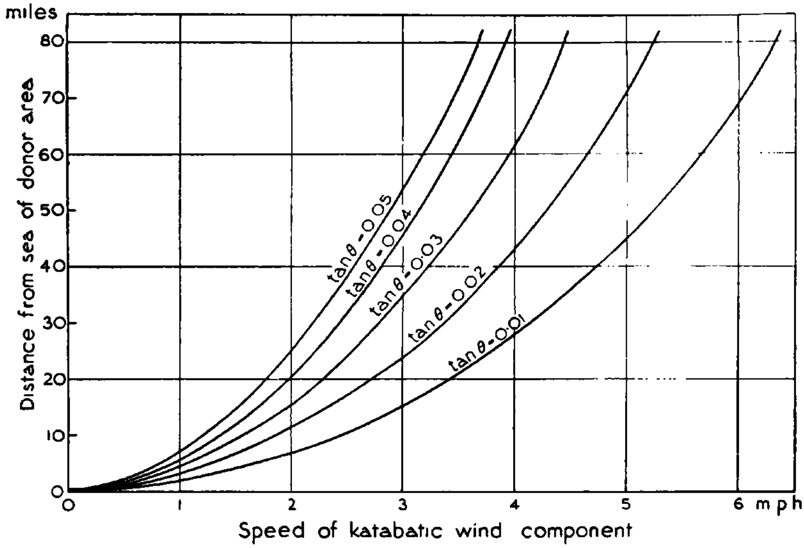


FIG. 3—RELATION OF SPEED OF KATABATIC FLOW TO DISTANCE FROM SEA AND ANGLE OF SLOPE OF LAND

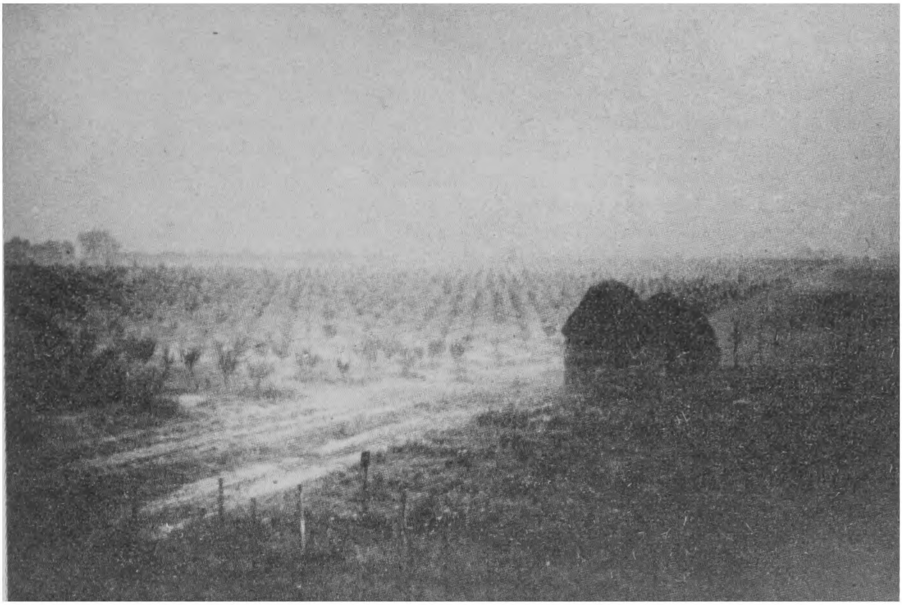
Assuming $$\overline{V} = \overline{K} + \overline{L},$$

therefore $$\overline{V} = \sqrt{\left\{\frac{2x}{1 \cdot 4 + 100 \tan \theta}\right\}} + \overline{L}.$$

This formula gives the resultant nocturnal wind in terms of the slope, the distance of the donor area from the sea, plus the land-breeze component which may be obtained from Fig. 2. The size of the donor area is discussed below under the headings of katabatic winds in valleys and length of slope. Limitations on the value of θ for which this formula holds are discussed in the next paragraph.

Slope of land.—From this relationship and also from the actual scatter of the plotted observations, it is clear that in a certain range of slopes the katabatic wind decreases with increasing slope. This does not appear to be in complete agreement with the theoretical results obtained by Jeffreys[2] who arrived at the conclusion that " the steeper the hill, the faster the mountain wind." In his paper it was assumed that the atmosphere was incompressible. However, the observations and general formula appear to be consistent with the theoretical results obtained by Prandtl[6] and Fleagle[7], who, assuming air compressibility, found that the maximum possible drainage velocity is directly proportional to the cosine (Prandtl) or cotangent (Fleagle) of the angle of the slope ; the assumption implies that, for steep slopes where the vertical drop per unit length of ground track is greater than for slight slopes, the increased adiabatic warming tends to neutralize the effect of cooling by the ground.

The effect of slope is illustrated in Fig. 4, a photograph taken in an orchard of Thomas Neame at Throwley, Faversham. The site is in a high position on the North Downs with the main slope down towards the north. The track ABCDE is a cold air drain with a shallow concavity down which cold air is flowing. The air flow is shown by the movement of thick mist down the slope AB. The mist builds up on the roughly horizontal surface BC and overflows down the slope CDE. Along the slope CDE, which is steeper than AB, the mist



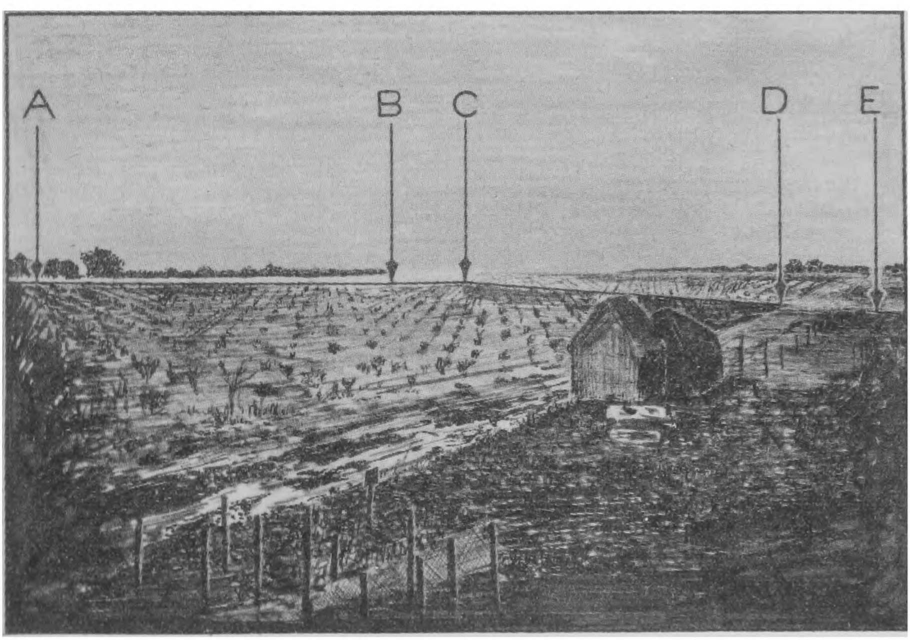
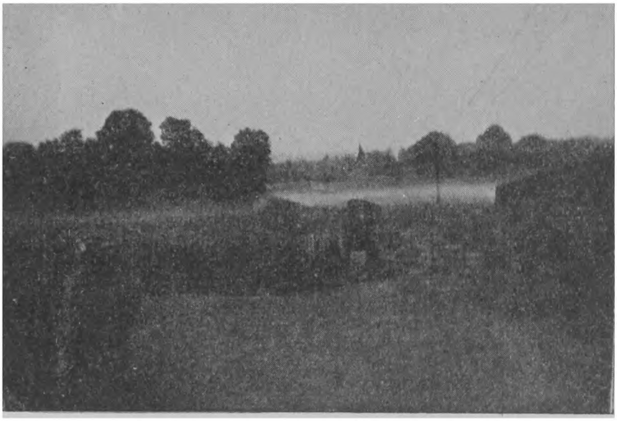


FIG. 4—THROWLEY, FAVERSHAM, KENT, NOVEMBER 1949, 0730 G.M.T.

The photograph shows the effect of slope on the development of mist along a shallow cold air drain. A, B, C, D, E indicate the sections of the cold air drain.

To face p. 7]



Reproduced by courtesy of the Ministry of Agriculture

FIG. 5—" RIVER MIST " IN A MEADOW IN A VALLEY, SEPTEMBER 29, 1937, 1818 G.M.T.

The mist moves with the katabatic air, thus rendering the motions of the latter visible. The mist river is shown moving downhill to the left and pouring over a stone wall 6 ft. high.

appears thinner. Another interesting photograph, Fig. 5, published in *Agriculture*[8], shows a river of mist moving down a gentle slope and surmounting a wall.

The graphs (see Fig. 3) and formulæ (given above) show that, although below a certain value of θ in the range $0 \cdot 01 > \tan\theta > 0$ katabatic winds do not occur, the magnitude of the katabatic wind increases with decreasing slope. The maximum value of K is reached when $\tan\theta$ is about 0·01. There were insufficient sites in category (*b*) to give a reliable estimate of the critical value for the slope below which katabatic winds do not occur, but it appears to be somewhere in the neighbourhood of 1 in 100 to 1 in 150. In this connexion Young[9] states that a slope of nearly 3 in 100 is necessary for air drainage to be effective in retarding the drop of temperature on a clear calm night on a broad uniform slope.

Further information on critical slope may be derived from Geiger's experiments[10] in which he measured temperatures at a height of 2 in. (5 cm.) on a " frost flat " (with slight slopes) near Anzing and observed differences of the order of 10°F. at points differing by only 8–10 in. (20–25 cm.) in height within a distance of 100–130 ft. (30–40 m.). Geiger concluded that down-slope winds developed. On this assumption, katabatic winds will develop at a height of 2 in. (5 cm.) on a slope of the order of 1 in 150.

Soil and ground cover.—With reference to vegetation cover (such as grassland, fruit orchards, etc.), the effect of friction on light surface winds is not very important unless the obstruction be really dense and of sufficient height[8]. When a slope has a dense belt of vegetation the barrier has the same effect as a wall. If such a belt is orientated across the line of greatest slope, cold air will accumulate on the up-slope side until the approximate height of the barrier is reached, as in Fig. 5, unless the belt is provided with gaps at ground level through which the cold air can drain. On the down-slope side of the barrier the decrease in wind would lead to a greater lowering of temperature (see section below on conditions of flow), but moist soils would be less affected because of the reduced lowering of temperature by evaporation. There would be renewed development of katabatic flow further down slope on the lee side of the barrier.

It was found that the down-valley winds in snow-covered areas (e.g. the Highlands of Scotland) sometimes continued throughout the day. The glacier wind described by Tollner[11] is a similar phenomenon and blows most strongly on fine summer days.

Cornford[8] carried out experiments to show that air temperature depended on the surface (soil or crop) over which the air flowed. Similar results were obtained on sloping land in a katabatic wind of 2–3 m.p.h. For example, on July 7–8, 1937, in a small valley at Leckford, Hampshire, where the higher part was grassland and the lower part arable fields, it was found that temperature readings were 3·5°F. higher in some places in the lower part of the valley than over the grassland in the upper valley, notwithstanding the fact that air moved down the valley, all night, from the colder to the warmer part.

As katabatic winds are closely related to the distribution of temperature in the lowest layers, it may be expected that the nature of the ground cover would have an effect on the speed of a katabatic wind, but in the current investigation the effect of ground cover could not be determined as it was masked by more effective influences.

Katabatic winds in valleys.—During the investigation it was found that at category (*b*) stations there was a tendency for nocturnal drifts to flow from the direction of high ground in the neighbourhood. In a previous investigation[12], in which data for a great variety of sites were considered, there was found to be a distinct prevailing wind during conditions of radiation frost, though this flow was not always from the direction of the nearest high ground, but rather down the main valley near which the site was situated. It was evident that with narrow valley sites, included in category (*c*), the nocturnal flow is usually controlled by the neighbouring orography, and for this reason this type of site was excluded, as far as possible, from the investigation into the effects of slope.

In a study of the katabatic winds in the upper Thames Valley, Newnham[13] describes an example of a katabatic wind of speed 20 m.p.h. (9 m./sec.) at 2100 on April 29, 1915, in the centre of an anticyclone. Using Figs. 2 and 3 and taking a slope of 1 in 50 for the Benson region and distance from the sea as 70–80 miles, a wind of only 5 m.p.h. would be expected. The difference between the observed and calculated values appears to be due chiefly to the valley topography in the vicinity of Benson. The speed of katabatic winds in valleys will vary in proportion to the width of the valley, steepness of banks, etc., factors which may lead to the canalizing of the flow and which are one, at least, of the causes of gales in the fjords of Greenland. Conversely, in the case of convex slopes (e.g. spurs extending downwards from a hill) the nocturnal wind will have a speed below the value given by the formula.

Another example of a valley wind, which was studied by Heywood[3], occurs at a site near Leafield in a Cotswold valley. The length of the slope from the watershed to the site is one mile, giving an average gradient of 1 in 24 or 0·04. Taking the distance from the sea as 60–70 miles, the graphs of Fig. 3 give the value for K as approximately 3 m.p.h., a value which is very similar to the greatest hourly mean katabatic wind of 3·6 m.p.h. (1·6 m./sec.) at this site. This is far less than that observed at Benson[13], a fact which Heywood states is difficult to understand. An important difference between the sites lies in the different slopes of the valley itself and also in the different slopes of the valley banks. With a valley slope of 1 in 24 and even steeper banks the latter will supply much less cold air than the shallower banks at Benson, where the slopes are within the range of those which are associated with much larger katabatic winds.

Length of slope.—The sites examined within category (*b*) were selected as far as possible for their location on broad flat slopes away from summits and valley floors. The mean slopes usually extended over a distance of from ½ to 3 miles up wind. Within these limits, no material effect of length of slope was discernible.

On the basis of Reiher's assumption[14] that cold air flows only under the influence of gravity, a formula for speed of flow is obtainable as given by Geiger[10] :

$$K = \sqrt{(2g'h)},$$

where h is the height of fall and g' (the downward acceleration acting on the air mass) is given by

$$g' = \frac{(T' - T)\,g}{T'},$$

where g is the normal acceleration due to gravity and T, T' are the absolute temperatures of the cold air and the surrounding air respectively. Thus

$$K = \sqrt{\left\{\frac{2gh\,(T'-T)}{T'}\right\}}, \qquad \ldots\ldots (1)$$

and if l is the length of fall measured along the slope

$$K = \sqrt{\left\{\frac{2\,gl\,\sin\theta\,(T'-T)}{T'}\right\}}. \qquad \ldots\ldots (2)$$

Reiher found that equation (1) was confirmed in general by the results of his investigations, but he neglected air compressibility thereby obtaining a theoretical value for K which increases with increase of θ, a relationship which present observations show not to be the case. Furthermore, h involves l and θ, two distinct and independent variables. If then K does not increase with θ, it may increase with l. In practice it is difficult to find long slopes without an appreciable degree of surface concavity and associated confluence, which would give a larger value for K. Equation (2) may indicate the speed of the katabatic wind during its building-up stage when the slope length is insufficient for maximum katabatic flow.

Topography.—With reference to the magnitude of nocturnal winds, it has been stated that katabatic winds are controlled by the degree of slope and by the concavity (or convexity) of the surface. The magnitude of land-breezes, although primarily controlled by the distance from the sea, also appears to be influenced by topography. The map of Fig. 2 suggests that for areas surrounding large concavities in the coastline, like the Lancashire region, land-breezes may occur to a greater distance inland than on straighter coastlines, such as that of Lincolnshire ; where the area concerned is an area of confluence of land-breezes due to the influence of adjacent land masses (the Lancashire region is linked with the adjacent land masses centred over the Peak District and over Wales) there appears to be a stronger land-breeze. Land-breezes, like katabatic winds, tend to increase when canalized by valleys.

No examination of the magnitude of land-breezes to seawards of the coastline has been made in this investigation, but in an earlier study Goldie[15] found that the maximum nocturnal components (in the east–west direction) were about 2 m.p.h. at Bell Rock (about 12 miles from the mainland) and about 1 m.p.h. at Tiree (about 20–25 miles from the mainland). These values suggest that the isopleths of the magnitude of the land-breeze over the sea are roughly a " mirror " of those over land.

With regard to direction, it has been stated that katabatic winds flow directly down slope, but tend to be canalized by any marked valleys in the vicinity. Similarly, land-breezes flow directly from land to sea, approximately at right angles to the coastline, but where the coast has a major concavity the direction of the land-breeze in the vicinity appears to be deflected towards the direction of the axis of the concavity, e.g. south-easterly in the Lancashire region. This phenomenon may be regarded as a special case of the general canalization of land-breezes by valleys.

Height of ground.—In a previous investigation[12], no clear-cut relationship was found to exist between altitude and frequency of minima below, say, 32°F., but it was clear that orography and relative height were of prime importance. Similarly with katabatic flow, absolute height is probably not important ; but as far as relative height is concerned Geiger's observations[10] showed that a difference in land elevation of " only a few centimeters exerts a marked influence on the nocturnal temperature " and is probably associated with a slight katabatic drift.

It should be emphasized here that because land-breezes do not prevail to great heights (see p. 11), at least on isolated ranges of hills, resultant nocturnal winds may be dependent on absolute height in certain hilly coastal areas.

Meteorological conditions for nocturnal flow.—Radiative cooling of the earth's surface and cooling of the air near to this surface occurs particularly on cloudless nights, when there is no cloud to obstruct the outward radiation. On nights with strong pressure gradients winds are generally so high as to cause turbulent transfer of heat downwards from the layers above ; the cooling of the atmosphere, instead of occurring in a shallow surface layer, is spread over a thicker layer of the lower atmosphere, and the net cooling in the surface layer is thus much smaller and katabatic winds do not materialize. Clear nights with calms or light winds are therefore the two main conditions for the development of katabatic winds or land-breezes.

Cooling is usually more rapid in air of low humidity as there is no latent heat available to offset the radiative cooling. However, it is possible with higher humidities to have extremely marked katabatic effects associated with the formation of valley fog which reduces outgoing radiation from the valley floor, particularly by comparison with the slopes above the fog. An example of the latter effect[3] occurred on the night of January 6–7, 1931, at the site near Leafield, mentioned above, when the katabatic wind blew almost continuously throughout the night with the high speed of 9–11 m.p.h. (4–5 m./sec.).

It has been found that the conditions described as suitable for katabatic effects were usually associated with surface inversions of temperature ; the latter were, in effect, a good indication as to when to expect katabatic winds. However, in cases when there was an unusually large inversion, there was often no nocturnal wind but a dead calm. In this connexion, Heywood[3] states that " A katabatic wind was seldom observed at the same time as one of these big inversions ", i.e. when the temperature difference between 4 ft. and 100 ft. was more than 5°F. The building up of the inversion on high ground was often associated with a dead calm in the valley.

Regarding the simultaneous occurrence of big inversions with calm conditions the mechanism may be described as follows. Suppose there exists a steep negative lapse rate and that air on the slopes is being cooled by the ground. The temperature of this air may fall below that in the open at the same level and tend to move down slope, cooling further in the layer nearest the slope. Continued motion depends on whether the rate of cooling with decrease in height due to contact with the slope (and partly nullified by adiabatic warming) is numerically greater than the atmospheric lapse rate. If the inversion is sufficiently intense, this will not be the case. When the katabatic flow off the higher slopes ceases, the inversion is able to build up further over these areas.

It should be mentioned that katabatic winds may develop to some extent, when the general weather is dominated by wind or rain, in a particular locality which is well sheltered from the elements by dense tall trees. This was demonstrated by Geiger at Anzing[10].

Depth of flow.—Following the argument concerning big inversions, it might be expected that the depth of katabatic flow would decrease with decreasing lapse rate, i.e. with increasing inversion. Data are insufficient to confirm this generally. Estimation of flow thickness by means of tree damage in Kent led Cornford[8] to the conclusion that in sloping fields the upper level of the gravitationally moving layer tended to follow the contours. For example, trees standing at 150 ft. above sea level were damaged to a height of 30 ft., while those standing on much lower ground, at 100 ft. above sea level, were damaged to a height of 40 ft. In a valley bottom with no outlet for cold-air flow the damage may reach much greater heights, but there the flow ceases, and the stagnant cold air may build up to several hundred feet or more, according to the topography, as is often indicated by a pool of valley radiation fog. Wagner[16] quotes the depth of mountain valley winds as building up, sometimes, " to several hundred metres ". Near summits it may be expected that the depth of flow varies from zero thickness to a value comparable with that on the open slopes, usually thickening as it progresses downhill[4]. Heywood[3] often observed depths of 15 ft. while Richardson[17] tried to measure the mountain wind by means of pilot balloons and thought the depth was 330 ft. (100 m.) on one occasion. Schultz[18] in his studies of the " Wisper wind ", a nocturnal down-valley wind in the Wisper Valley which opens into the Rhine, found a depth of 330–500 ft. (100–150 m.).

That katabatic winds, even on the largest possible scale, affect only a comparatively shallow atmospheric layer may be inferred from observations from Greenland. At the base camp[19] on the east coast a wind of 129 m.p.h. was observed, while at Angmagssalik, a few miles away, only light or moderate winds were recorded, the energy of flow having been rapidly destroyed by friction and turbulent mixing.

According to Deacon[20], on radiation nights, that is on nights favourable for katabatic flow, the wind decreases with height and is often reversed. Observations taken by Reidel and summarized by Defant[21] showed that above a slope of 42·5° the maximum speed was reached at about 100 ft. (30 m.) and zero speed at about 330 ft. (100 m.) elevation.

The depth of land-breeze flow is not so easy to investigate without meteorological observations, as the top of the moving layer is well above the zone of growth in flat country. It is significant that Stonyhurst (height of station 377 ft., height of anemometer mast 55 ft.) did not have the prevailing south-easterly breeze shown by most Lancashire sites examined by Hawke[1], some of which were further inland. Brunt[22] states that land-breezes normally extend to a height of 200 ft. only.

Frequency of nocturnal winds and seasonal changes.—No material variation was observed in the frequency of occurrences of katabatic winds during the months examined. Heywood[3] confirms that the katabatic effect was not specially frequent at any particular season of the year. A clear short night in late spring or summer is just as likely to induce a katabatic flow as a long night in December or January.

Further, no large change was apparent in the magnitude of the katabatic flow during the months examined ; at times, the katabatic wind would reach its maximum quite early in the night. In snow-covered areas shaded from sunshine, for example the upper Spey valley in Scotland, katabatic winds sometimes continued to blow through the day.

Regarding land-breezes, a tendency was found in flat coastal areas for winds to increase during the night, but no discernible variations in frequency or in maximum speed were evident during the months March to May inclusive. It may be expected that the strength and frequency of land-breezes are greatest in autumn when the nights are rather long and when the contrast between cold land and warm sea is greatest.

Further characteristics of nocturnal winds.—Further properties of nocturnal winds may be observed from a study of anemograms. Wind-record traces often show sudden discontinuities in both magnitude and direction around dusk with the onset of the night wind and around dawn with the change to the day wind.

Records indicate that nocturnal winds are generally less gusty than day-time winds which are affected by convection.

During the building up of katabatic winds records sometimes show quite clearly the periodic nature of the wind, which, according to Defant[23], occurs on slopes at inclinations over 1 in 100. Examples given by Heywood[3] (and others) show that during the development stage (lasting 2 hr. in some cases) the period is of the order of 20 min.

Reiher[11] examined the temperature distribution on a steep slope (pitch 1 in 3) at Göttingen, and found that the down flow of cold air often occurred in bursts, repeated rhythmically every 4 or 5 min. The speed of the cold air was 3·1 m.p.h. (1·4 m./sec.) and the length of the burst of cold air about 1,000–1,300 ft. (300–400 m.).

Some of the properties of nocturnal winds are illustrated in the anemograms shown in Figs. 6–8. The heights of the anemometers at the three stations are as follows:

	Height of vane above M.S.L.	Height of vane above ground	Effective height
		feet	
Cardington ..	285	150	135
Fleetwood ..	112	50	31
Southport ..	60	42	33

Fig. 6 is the anemogram for Cardington on May 22–23, 1952, when the whole of the British Isles was covered by an anticyclone (1032–1035 mb.). This site, situated near the centre of the land mass and about 60 miles from the sea, can have little or no land-breeze and the south-south-easterly nocturnal wind between 2000 and 0200 G.M.T. may therefore be regarded as a slope wind.

Fig. 7 shows the wind record for Fleetwood (Lancashire) on May 15–16, 1946, when there was a weak north-westerly gradient over this area during the night. At 0600 G.M.T. May 16, Jurby reported NW. force 3 and Spurn Head reported W. force 3 but Fleetwood recorded a south-easterly wind from about 2100 to 0800. During the first 2 hr. after dusk (i.e. 1900–2100) there was a gradual veer from NW. to SE., but at 0800 (i.e. about 3 hr. after dawn) the change from SE. back to NW. was rather sudden. The south-easterly wind commenced with a light burst of speed. The land around Fleetwood is rather flat and this wind was probably a land-breeze, canalized a little by the estuary of the Wyre.

Fig. 8 is the Southport wind record for the same day as that of Fig. 7. Here again, the north-westerly surface wind due to the gradient is reversed to south-easterly from about 2100 to 0800 G.M.T. (though almost calm during the last hour of this period). As at Fleetwood, the south-easterly wind commenced at about 2100 with a burst. At Southport, this burst was much more marked and associated with a sudden change in wind direction from north-westerly to south-easterly, as distinct from the gradual veer at Fleetwood from 1900 to 2100.

Nocturnal flow and damage to crops.—Damage to vegetation often extends to the top of the nocturnal flow or to the upper level of the stagnant cold-air pool in valleys or hollows. Where temperature approaches the critical value for a particular species of vegetation, the extent of damage must depend on the speed of flow, for with higher speeds the penetrating effect is much greater.

The association of nocturnal flow with frost damage is shown by the distribution of damage caused by the frosts of May 1935[24]. In Norfolk the main area of frost damage was inland, and reports of damage from the coast were confined to that part of the coast where the East Anglian Heights extend near to it and where the ground rises to 327 ft. within about 2 miles of the sea. Again, in Suffolk the position was similar, the coastal damage occurring in the south of the county, where the East Anglian Heights are nearer the coast; further, on the southern coast of south-eastern England, damage reports appear to be associated with the areas where the North and South Downs reach the coast. The dangerous periods of May 1935 were not confined to radiation frosts, but if the damage caused had been predominantly " wind frost " damage, the map of damage distribution would have shown a closer relationship between damage and high ground. It is considered that the variation in coastal damage was associated with the nocturnal winds which occur with radiation frosts, and that damage was more likely to have occurred where the land-breeze was reinforced by katabatic flow.

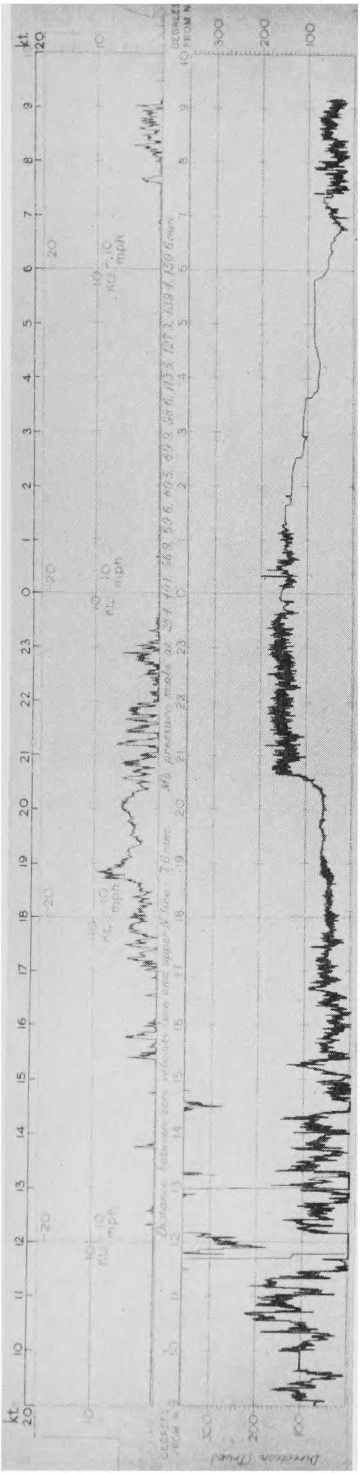


FIG. 6—ANEMOGRAM, CARDINGTON, MAY 22–23, 1952

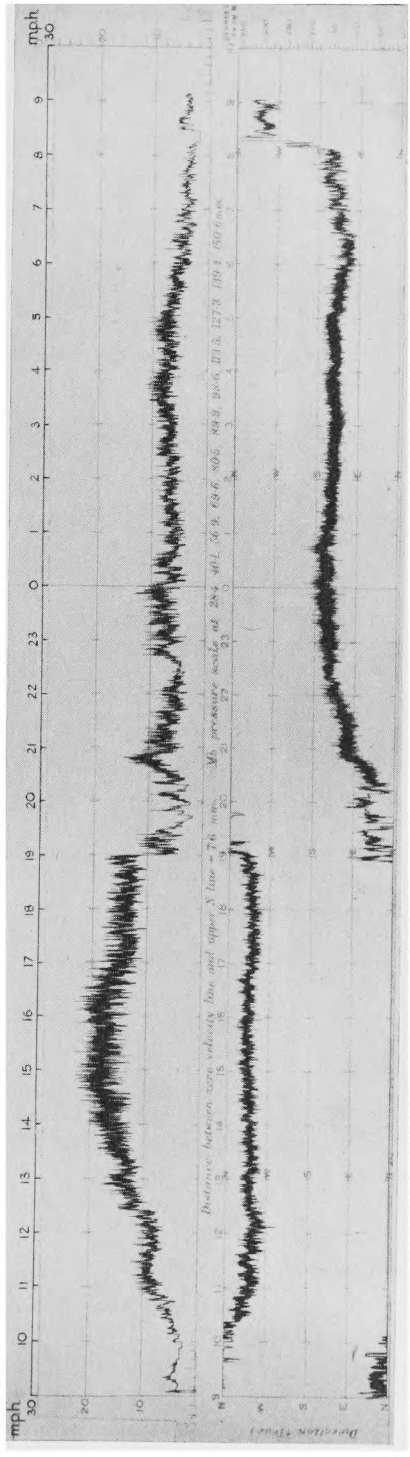


FIG. 7—ANEMOGRAM, FLEETWOOD, MAY 15–16, 1946

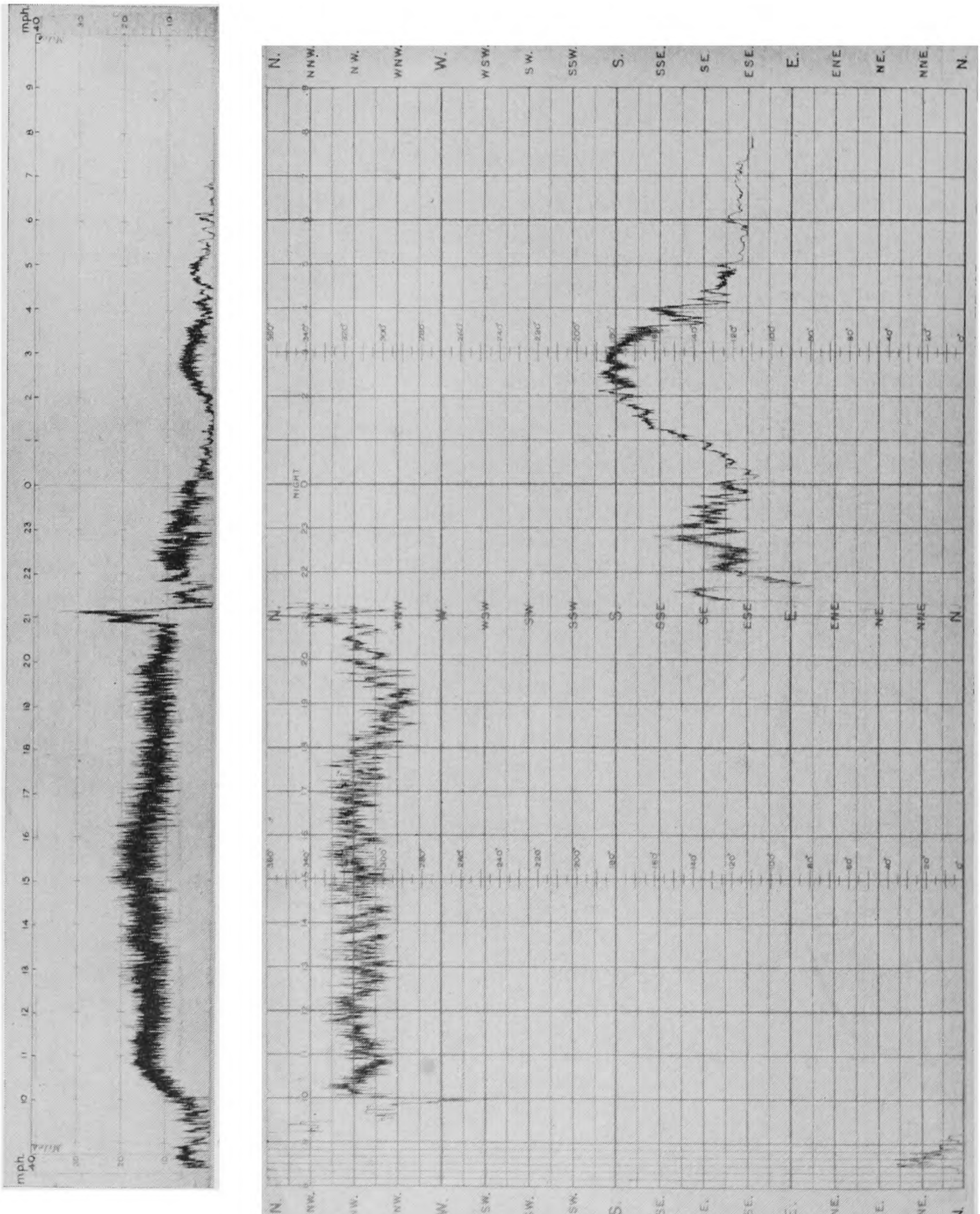


FIG. 8—ANEMOGRAM, SOUTHPORT, MAY 15–16, 1946

BIBLIOGRAPHY

1. HAWKE, E. L.; The land-breeze of autumn and winter in north-west England. *Quart. J. R. met. Soc., London*, **67**, 1941, p. 381.
2. JEFFREYS, H.; On the dynamics of wind. *Quart. J. R. met. Soc., London*, **48**, 1922, p. 29.
3. HEYWOOD, G. S. P.; Katabatic winds in a valley. *Quart. J. R. met. Soc., London*, **59**, 1933, p. 47.
4. BRUNT, D.; Some factors in micro-climatology. *Quart J. R. met. Soc., London*, **71**, 1945, p. 1.
5. BUSH, R.; Frost and the fruitgrower. London, 2nd edn, 1946.
6. PRANDTL, L.; Führer durch die Strömungslehre. Braunschweig, 1942.
7. FLEAGLE, R. G.; A theory of air drainage. *J. Met., Lancaster Pa*, **7**, 1950, p. 227.
8. CORNFORD, C. E.; Frost and fruit-growing. *Agriculture, London*, **45**, 1939, p. 981.
9. YOUNG, F. D.; Frost and the prevention of frost damage. Washington, 1947.
10. GEIGER, R.; The climate near the ground. Cambridge Mass., 1950.
11. TOLLNER, H.; Gletscherwinde in den Ostalpen. *Met. Z., Braunschweig*, **48**, 1931, p. 414.
12. LAWRENCE, E. N.; Frost investigation. *Met. Mag., London*, **81**, 1952, p. 65.
13. NEWNHAM, E. V.; Notes on examples of katabatic wind in the valley of the upper Thames at the aerological observatory of the meteorological office at Benson, Oxon. *Prof. Notes met. Off., London*, **1**, No. 2, 1918.
14. REIHER, M.; Nächtlicher Kaltluftfluss an Hindernissen. *Bioklim. Beibl., Braunschweig*, **3**, 1936, p. 152.
15. GOLDIE, A. H. R.; Wind records from the Bell Rock Lighthouse. *Geophys. Mem., London*, **7**, No. 63, 1935.
16. WAGNER, A.; Theorie und Beobachtung der periodischen Gebirgswinde. *Beitr. Geophys., Leipzig*, **52**, 1938, p. 408.
17. RICHARDSON, L. F.; Discussion on " On the dynamics of wind ". *Quart. J. R. met. Soc., London*, **48**, 1922, p. 47.
18. SCHULTZ, H.; Über Klimaeigentümlichkeiten im unteren Rheingau, unter besonderer Berücksichtigung des Wisperwindes. *Frankfurt. geogr. Hft., Frankfurt am Main*, **7**, Heft 1, 1933.
19. WATKINS, H. G.; The British arctic air route expedition 1930–31. *Geogr. J., London*, **79**, 1932, p. 466.
20. DEACON, E. L.; Vertical profiles of mean wind velocity in the surface layers of the atmosphere. *Geophys. Mem., London*, **11**, No. 91, 1953.
21. DEFANT, F.; Zur Theorie der Hangwinde, nebst Bemerkungen zur Theorie der Berg- und Talwinde. *Arch. Met., Wien*, A, **1**, 1949, p. 421.
22. BRUNT, D.; Physical and dynamical meteorology. Cambridge, 2nd edn, 1939 reprinted 1941, p. 281.
23. DEFANT, A.; Der Abfluss schwerer Luftmassen auf geneigtem Boden nebst einigen Bermerkungen zu der Theorie stationärer Luftströme. *S.B. preuss. Akad. Wiss., Berlin*, 1933, p. 624.
24. Forestry Commission. Spring frosts. *Bull. For. Comm., London*, No. 18, 2nd edn, 1946.

(62357) Wt. 4216/B.M.4301 K.6 6/54 Hw.

PRINTED AND PUBLISHED BY HER MAJESTY'S STATIONERY OFFICE

To be purchased from

York House, Kingsway, LONDON, W.C.2 423 Oxford Street, LONDON, W.1

P.O. Box 569, LONDON, S.E.1

13a Castle Street, EDINBURGH, 2 1 St. Andrew's Crescent, CARDIFF

39 King Street, MANCHESTER, 2 Tower Lane, BRISTOL, 1

2 Edmund Street, BIRMINGHAM, 3 80 Chichester Street, BELFAST

or from any Bookseller

1954

Price 1*s* 0*d* net

PRINTED IN GREAT BRITAIN

S.O. Code No. 40-57-11-1