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DOWNWARD PENETRATION OF SNOW IN RELATION TO THE INTENSITY OF PRECIPITATION

By F. E. LUMB

"For he saith to the snow; fall thou on the earth."

Job xxxvii, vi

Summary.—By a combination of theory and observation, a simple relationship between the potential depth of penetration of snow and the intensity of the precipitation is derived, which shows that during prolonged frontal precipitation in a synoptic situation favourable to the downward penetration of snow, snow will descend beyond the 2°C wet-bulb level, but is unlikely to penetrate beyond the 2.5°C wet-bulb level. Within extensive areas of moderate to heavy instability precipitation, snow will probably descend to the 3.0°C wet-bulb level, but is very unlikely to penetrate beyond the 3.5°C wet-bulb level.

Introduction.—As explained in an earlier paper dealing with the problem of forecasting the downward penetration of snow,[1] once a substantial amount of falling snow (in the form of melting snow-flakes) reaches the ground, cooling of the whole column of air between the 0°C level and the ground by the melting of the falling snow is initiated, and the rate of cooling may become rapid once the form of precipitation is observed as sleet.* Unless the cooling by melting is counteracted by the advection of warmer air, it can quickly reduce the temperature of the whole layer to 0°C. Precipitation then takes the form of snow at all levels down to the ground. The purpose of this paper is to find a simple relationship between the potential depth of penetration of snow and the intensity of the precipitation, and apply it to the problem of forecasting snow.

Melting depth of snowflakes in relation to melted drop size.—R. Wexler[2] has derived theoretically the following expression relating the distance (Z) which snow-flakes (assumed to be spherical in shape) have fallen below the 0°C level in saturated air, to the fraction (F) of the mass of snow-flakes which has melted:

$$m \int_0^F V^2 \, dF = 2\pi A \gamma C D_r V_r \int_0^Z Z \, dZ \qquad \ldots\ldots \text{(1)}$$

*Throughout this paper the word "sleet" means precipitation in the form of raindrops and melting snow-flakes.

where

m is the mass of the snow-flake (during the period of melting m increases by condensation by about six per cent but can be assumed constant without serious error).

V is the speed of fall at a distance Z below the 0°C level.

V_0 is the speed of fall at the 0°C level.

V_r is the terminal speed of the melted drop.

D_r is the diameter of the melted drop.

C is a ventilation coefficient (a function of the Reynolds Number, Re, of the melted drop).

γ is the lapse rate (assumed constant).

A is effectively a constant which incorporates the latent heats of fusion and evaporation, the thermal conductivity of air, and the diffusion coefficient of water vapour in air.

As shown by Wexler,[2] if it is assumed that the melted portion of the snow-flake is absorbed into the ice portion until its diameter is equal to that of the raindrop, then the relationship

$$V = V_0 (1 - F)^{-\frac{1}{3}} \qquad \ldots\ldots (2)$$

holds good until the snow-flake is almost completely melted. Wexler[2] has used equations (1) and (2) to calculate the distance below the 0°C level at which the snow-flakes are completely melted (using the relation $V = V_r$ when $F = 1$), but for present purposes we need to express Z in terms of F. Substituting for V from equation (2) in equation (1) and integrating we get

$$Z = \left[\frac{3mV_0^2}{\pi A\gamma CD_rV_r} \left\{ 1 - (1 - F)^{\frac{1}{3}} \right\} \right]^{\frac{1}{2}} \qquad \ldots\ldots (3)$$

Wexler[2] has also considered snow-flakes which are disk-shaped on arriving at the 0°C level and are assumed to retain this shape during melting. For these, the equation corresponding to equation (1) is:

$$m \int_0^F V^2 \, dF = 4A\gamma CD_rV_r \int_0^Z Z \, dZ \qquad \ldots\ldots (4)$$

where $V = V_0 (1 - F)^{-\frac{1}{2}}$ ...... (5),
equation (5) being valid until the snow-flake is almost completely melted.

Again, in order to express Z in terms of F, we substitute for V from equation (5) in equation (4) and integrate to get:

$$Z = \left[\frac{mV_0^2}{2A\gamma CD_rV_r} \log (1 - F)^{-1} \right]^{\frac{1}{2}} \qquad \ldots\ldots (6)$$

Equations (1) and (4) were derived on the assumption that the snow-flakes are impervious to the airflow. Since we are concerned here with periods of precipitation lasting several hours, then except perhaps during the first hour or two the snow-flakes will be falling through thick cloud layers throughout most if not all of their descent to the 0°C level, and will therefore arrive at this level in a rimed condition. It has been shown elsewhere[3] that any percolation of air through falling rimed snow-flakes is very small. Hence Wexler's assumption that the snow-flakes are impervious to the air throughout the period of melting should not lead to any serious error.

In reality, snow-flakes do not conform to any simple geometrical shape, and their shape changes as they melt. However, the deviation of the shape

Photograph by D. J. George

LIGHTHOUSE AT CAPE WRATH, SUTHERLAND, LOOKING NORTH-WEST

The lighthouse was built in 1828, and since 1940 has been an auxiliary meteorological station equipped with standard instruments and reporting three-hourly. The light is 204,000 candle-power and can be seen in clear weather by ships 27 miles away. In this photograph the temperature readings are being taken by Keeper J. Budge.

[*To face p. 2*

Photograph by D. J. George

LIGHTHOUSE AT RUDH RE, WESTER ROSS, LOOKING NORTH

The station was built in 1912. It has been an auxiliary meteorological station since 1940. The light is 295,000 candle-power and is visible 17 miles away in clear weather. The above photograph, and the photographs opposite page 35, are reproduced by kind permission of the Secretary, Northern Lighthouse Board.

of a real snow-flake from that of a spherical one of the same mass can be taken into account by incorporating in the left-hand side of equation (1) a correction factor, X. If X_0 is the value of X when $F = 0$, then $X = X_0\varphi(F)$, where $\varphi(F)$ is a finite and continuous function of F. For snow-flakes arriving at the 0°C level with any prescribed shape, X_0 is a constant, and the modified form of equation (1) for such snow-flakes is

$$X_0 m V_0^2 \int_0^F (1-F)^{-\frac{2}{3}} \varphi(F)\,dF = 2\pi A\gamma C D_r V_r \int_0^Z Z\,dZ \qquad \ldots\ldots (7)$$

$$\text{whence } Z = \left[\frac{X_0 m V_0^2}{\pi A\gamma C D_r V_r} \int_0^F (1-F)^{-\frac{2}{3}} \varphi(F)\,dF\right]^{\frac{1}{2}} \qquad \ldots\ldots (8)$$

As pointed out by Wexler,[2] some measurements by Langleben[4] of the speed of fall of wet snow-flakes at a temperature of 35°F (1.7°C) imply that the snow-flake retains its characteristic appearance until at least 90 per cent of its mass has melted. Hence if we substitute $F = 0.9$ in equations (3) and (6) we get an approximation to the greatest distance, $Z_{0\cdot 9}$, below the 0°C level at which the form of precipitation should be observable as sleet, assuming spherical and disk-shaped snow-flakes respectively.

As explained earlier m can be regarded as constant without serious error, that is

$$m = \frac{\pi}{6} D_r^3 \qquad \ldots\ldots (9)$$

Also, according to measurements by Langleben[4] of the terminal speeds of aggregate snow-flakes over the range of D_r from 0.4 to 3.5 mm,

$$V_0 = k D_r^{0\cdot 31} \qquad \ldots\ldots (10)$$

where k depends on the structure of the snow-flakes. For rimed dendrites, Mason[5] gives the value of k as 221, and this value has been adopted in calculating $Z_{0\cdot 9}$. Values of C measured for raindrops by Kinzer and Gunn[6] show that, for drop diameters between 0.5 and 4 mm, C can be adequately represented by the expression $(1 + 0.21\,\text{Re}^{\frac{1}{2}})$.

Hence by means of equations (9) and (10) m and V_0 can be eliminated from equations (3) and (6), and since C is a function of Re, $Z_{0\cdot 9}$ can be expressed as a function of D_r, V_r, Re and γ only. Using corresponding values of D_r, V_r and Re taken from the *Smithsonian Meteorological Tables*, 6th edition, values of $Z_{0\cdot 9}$ have been calculated for values of $D_r = 0.5$, 1·0, 2·0, 3·0, 4·0 mm when γ is the saturated-adiabatic lapse rate, γ_s. They are marked in Figure 1 by small open circles. The relationship between $Z_{0\cdot 9}$ and D_r is seen to be very nearly linear and, denoting $Z_{0\cdot 9}$ by $Z_{0\cdot 9}^{(s)}$ when $\gamma = \gamma_s$, the equations to the best-fitting straight lines are:

$$Z_{0\cdot 9}^{(s)} = 79\cdot 6\, D_r + 69\cdot 0 \text{ (spheres)} \qquad \ldots\ldots (11)$$

$$Z_{0\cdot 9}^{(s)} = 119\cdot 7\, D_r + 102\cdot 5 \text{ (disks)} \qquad \ldots\ldots (12)$$

where $Z_{0\cdot 9}^{(s)}$ is expressed in metres and D_r in mm.

It can readily be deduced from equations (3) and (6) that as D_r varies the values of $Z_{0\cdot 9}^{(s)}$ for spheres and for disks bear a constant ratio to each other. Hence the two straight lines given by equations (11) and (12) must meet on the D_r axis (at the point P in Figure 1) and equations (11) and (12) are represented in Figure 1 by the lines PQ, PR, respectively.

It is not possible to calculate $Z_{0\cdot 9}^{(s)}$ for real snowflakes since $\varphi(F)$ is unknown. However, from a study of the shape and structure of falling snow-flakes based

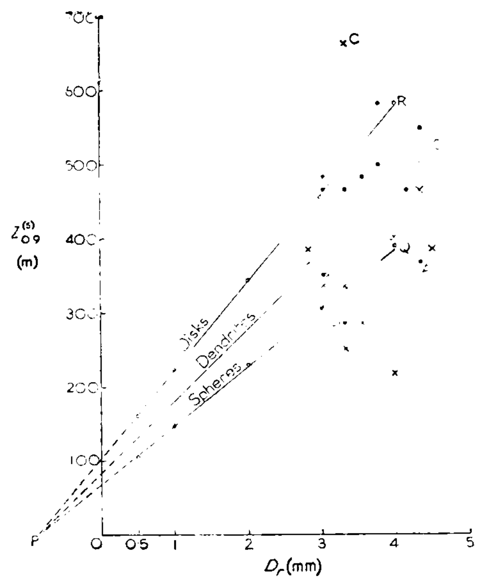

FIGURE I—RELATIONSHIP BETWEEN THE MELTED DROP DIAMETER (D_r) OF A SNOW-FLAKE AND THE DISTANCE $(Z_{0.9}^{(s)})$ BELOW THE 0°C LEVEL AT WHICH IT IS 90 PER CENT MELTED IN A SATURATED ATMOSPHERE WITH A SATURATED-ADIABATIC LAPSE RATE.

on many photographs, Magono and Oguchi[7] have concluded that large snow-flakes during snowfall at temperatures near 0°C are usually of dendritic type, whose horizontal dimensions are large in relation to their thickness. Hence as a rough approximation a large dendritic snowflake can be regarded as having the shape of a disk on arriving at the 0°C level. Since these snow-flakes are roughly disk-shaped when $F=0$, and since it is reasonable to suppose that they are more nearly spherical when $F=0{\cdot}9$, one can expect that $Z_{0.9}^{(s)}$ will be intermediate between the values for disk-shaped and spherical snow-flakes. Also it follows from equations (3) and (8) that, as D_r varies, $Z_{0.9}^{(s)}$ bears a constant ratio to $Z_{0.9}^{(s)}$ for spheres. Hence the relation between $Z_{0.9}^{(s)}$ and D_r for large dendrites should approximate to a straight line concurrent with but intermediate between the lines PQ and PR in Figure 1. Its equation will be

$$Z_{0.9}^{(s)} = a\,D_r + b \qquad \ldots\ldots (13)$$

where, by equation (11), $b/a = 0{\cdot}87$.

Potential depth of penetration of snow in relation to intensity of precipitation.—Gunn and Marshall[8] have given details of the average observed distribution of melted drop diameters during fifteen snowfalls divided into four groups for which the equivalent rates of rainfall (I) were 0·31, 0·70, 1·1 and 2·5 mm hr^{-1}. The largest drop diameter (D_r^*) for each average observed distribution was respectively 1·9, 2·5, 2·9 and 3·9 mm. In Figure 2, log D_r^* is plotted against log(10I) and we find an almost exactly linear relationship represented by the equation:

$$\log D_r^* = 0{\cdot}339 \log(10\,I) + 0{\cdot}112 \qquad \ldots\ldots (14)$$

whence we get, to a sufficient degree of accuracy,

$$D_r^* = 2{\cdot}83\, I^{0{\cdot}34} \qquad \ldots\ldots (15)$$

where D_r is expressed in mm and I in mm hr^{-1}.

If now we substitute for $D_r{}^*$ from equation (15) in equation (13)

$$\text{Max } Z_{0.9}^{(s)} = 2 \cdot 83a\, I^{0 \cdot 34} + b \qquad \ldots\ldots \quad (16)$$

where Max $Z_{0.9}^{(s)}$ is the distance (in metres) below the 0°C level at which the largest snow-flakes are just 90 per cent melted, and this level will approximate to the lowest level at which the precipitation can be recognized to be in the form of sleet.

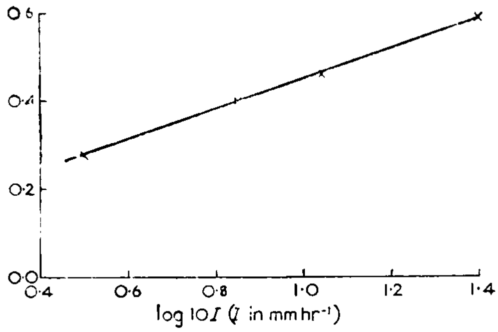

FIGURE 2—RELATION BETWEEN LARGEST MELTED-DROP DIAMETERS ($\log D_r^*$ IN MM) AND THE INTENSITY OF PRECIPITATION ($\log 10\, I$)

If T_s is the temperature corresponding to any distance Z below the 0°C level when the lapse rate is γ_s, equation (16) can be written in the form:

$$T_s = 0 \cdot 17\, a\, I^{0 \cdot 34} + 0 \cdot 06b \qquad \ldots\ldots \quad (17)$$

(T_s in °C, I in mm hr $^{-1}$).

For any given value of I, equation (17) gives the potential depth of penetration of snow in terms of the surface temperature, assuming a saturated environment and a saturated-adiabatic lapse rate.

Determination of the relationship between surface wet-bulb temperature and the intensity of precipitation.—In order to find numerical values for a and b, it is necessary to appeal to observations. The straight line given by equation (13) is required to separate cases of continuous rain from cases of continuous precipitation whose form changes from rain to sleet. Over the British Isles serious cases of rain changing to sleet, then snow, in the absence of cold air advection, i.e. cases when by the processes of cooling by evaporation and by melting of falling snow, snow extends down to or very near to sea level, are most likely to occur near to but on the cold side of the track of an active frontal depression or near the track of a polar low where, as demonstrated later in this paper, a rate of rainfall in excess of 1 mm hr^{-1} is liable to persist for several hours. The observations used were therefore restricted to occasions when the rate of rainfall was $\geqq$ 1 mm hr^{-1}.

(*a*) *Cases of precipitation whose form remained as rain.*—Using data for London (Heathrow) Airport* during the period 1949-58, occasions were extracted when rain fell continuously throughout a period of at least one tabular hour, and the following conditions were satisfied:

(T_w = surface wet-bulb temperature and
R = amount of rain during the hour
(i) $T_w < 3 \cdot 0$°C and $R \geqq 1$ mm
or $T_w < 4 \cdot 0$°C and $R \geqq 2$ mm
(ii) T_w did not decrease by more than $0 \cdot 5$°C during the hour.

*The positions and altitudes (in metres) of all observing stations (surface or upper air) mentioned in this paper are shown in Figure 11.

In order to make the test as stringent as possible, the lowest value of T_w reported during the hour (using half-hourly readings) was plotted against the highest rate of rainfall (averaged over 15 minutes). The resulting points are marked with a small black circle in Figure 3. Also, D_r* was calculated for each occasion using equation (15) and the values plotted against $Z^{(s)}_{0.9}$ in Figure 1 (small black circles).

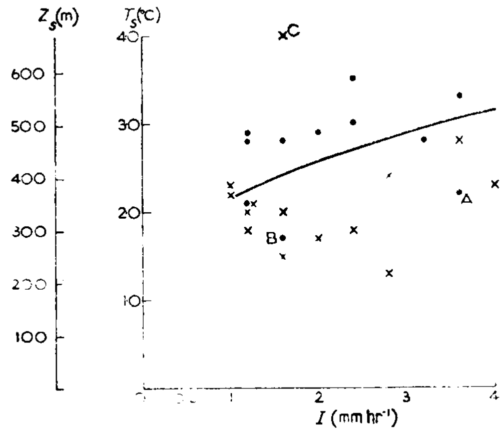

FIGURE 3—RELATION BETWEEN DEPTH OF PENETRATION OF SNOW AND THE INTENSITY OF MODERATE PRECIPITATION

(*b*) *Cases of precipitation whose form changed from rain to sleet.*—Occasions for Heathrow and Manchester Airports during the years 1949–58 when continuous precipitation lasting for at least one hour had changed its form from rain to sleet were extracted. A difficulty is that with the onset of sleet, the dry- and wet-bulb temperatures are liable to fall quickly towards 0°C, so that the wet-bulb temperature at the *reported* time of onset of sleet is very dependent on the vigilance of the observer. Therefore in order to make the test as stringent as possible the wet-bulb temperature at the last half-hourly observation before the reported time of onset of sleet has been plotted against the rate of rainfall averaged over the 15 minutes prior to the reported time of start of sleet. The resulting points are marked with a cross in Figure 3. Also, D_r* was calculated for each occasion using equation (5), and the values plotted against $Z_{0.9}$ as crosses in Figure 1.

The required straight line in Figure 1 for determining *a* and *b* is the one which most effectively separates the black circles from the crosses. A clear-cut separation is not to be expected, since equation (15) represents a statistical, not a functional relationship, between D_r* and *I*. The line PS is seen to be quite effective in separating the crosses from the circles. It was chosen so that no circle or cross was on the wrong side of the line by more than 30 metres, with the marked exception of the points A, B and C.

The equation of PS is

$$Z^{(s)}_{0.9} = 96{\cdot}5\, D_r + 84{\cdot}0 \qquad \ldots\ldots \quad (18)$$

whence from equation (17)

$$T_s = 1{\cdot}64\, I^{0{\cdot}34} + 0{\cdot}50 \qquad \ldots\ldots \quad (19)$$

The graph of equation (19) is shown in Figure 3 for the range of *I* from 1·0 to 4·0 mm hr⁻¹. For any given value of I, the curve gives the potential depth of penetration of snow in terms of the surface temperature, assuming a saturated environment and a saturated-adiabatic lapse rate.

Of the 11 cases of rain, two (marked A and B) lie well below the curve, and of the 15 cases of sleet, one lies well above the curve (point C). These occasions need closer investigation.

Rain 2200–2300 GMT, 31 *January* 1950 (*point A*).—Synoptic charts show that a wave on a trailing cold front formed near the Channel Isles about 1200 GMT on 31 January 1950. It moved up the English Channel and was centred over the Netherlands by 0600 GMT on 1 February. The most appropriate upper air sounding of the air through which the rain fell at Heathrow is that for Downham Market at 1500 GMT on 31 January shown in Figure 4. The wet-bulb curve

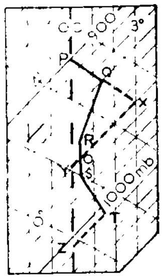

FIGURE 4—TEPHIGRAM SHOWING WET-BULB TEMPERATURE AT DOWNHAM MARKET AT 1500 GMT, 31 JANUARY 1950

is lettered PQRST. By the equal-area construction explained in reference (1) the surface value of T_s is the temperature given by point X such that area QXOR = area YOSTZ, that is 3°C. Referring to Figure 3, we see that if allowance is made for the stable wet-bulb lapse rate, point A is transferred to a position very close to the curve, which indicates that this was a critical case for downward penetration of snow. Snow did in fact descend almost to sea level in some places, for example Felixstowe where continuous moderate snow was reported at 0000 GMT on 1 February.

Rain 0100–0200 GMT, 19 *December* 1952 (*point B*).—Synoptic charts show that a warm front orientated approximately north–south was approaching Heathrow from the west. In Figure 5, LMN is the temperature sounding (with saturated air) at Larkhill just ahead of the warm front at 0300 GMT

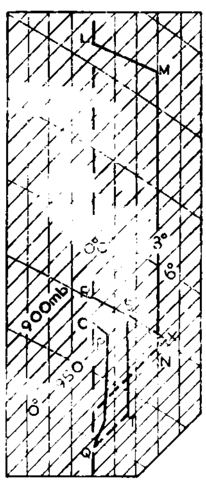

FIGURE 5—TEPHIGRAM SHOWING WET-BULB TEMPERATURE AT 0300 GMT, 19 DECEMBER 1952

LMN	Larkhill.	OPQ	Hemsby.
RST	London (Heathrow) Airport (interpolated).		

on 19 December 1952, and OPQ the wet-bulb curve at Hemsby at the same time. There is a deep isothermal layer extending down to the surface at both places. At Heathrow between 0200 and 0300 GMT the surface air was almost saturated with a wet-bulb temperature of 35·0°F (1·7°C), and with a surface pressure of 1005·0 mb it is reasonable to assume that the temperature at Heathrow between 0200 and 0300 GMT at any level up to the 0°C level was not less than that given by curve RST in Figure 5. By the equal-area construction the surface value of T_s is given by the temperature at point X, that is, it was not less than 3·5°C. Referring to Figure 3, after making allowance for the isothermal layer the point B is transferred well above the critical curve, and the fact that rain did not change to sleet in spite of the low surface temperature is explained.

Sleet at 0947 GMT, 8 *December* 1954 (*point C*).—Of the 15 cases of sleet, only one lies well above the curve (point C). This was an occasion of sleet at Heathrow on 8 December 1954. Synoptic charts show that the precipitation was associated with the approach from the west of the active occlusion of a deep depression off south-west Ireland. Sleet was first reported at 0947 GMT when I was 1·6 mm hr^{-1}, but soon afterwards I increased to 3·2 mm hr^{-1} between 1015 and 1030 GMT, and 5·6 mm hr^{-1} between 1045 and 1100 GMT. Also heavy rain or sleet was reported ahead of the occlusion at several places scattered over England. Hence there is strong evidence that the precipitation was of an instability type, and the occurrence of sleet with a wet-bulb temperature as high as 39·1°F (3·9°C) when I was only 1·6 mm hr^{-1} is very probably explained by the presence of some very large snow-flakes characteristic of instability precipitation. It has been shown in an earlier paper[1] that such snow-flakes may occasionally penetrate more than 700 metres below the 0°C level (corresponding to T_s = 4·2°C) and still be recognizable as snow-flakes.

Data presented by Mason and Andrews[9] point to the large differences which exist between the size-distribution of raindrops falling from cloud systems formed by different physical processes. There is no reason to doubt that this also applies to the melted drop size distributions of snow-flakes, and that therefore the relation between T_s and I given by equation (9) is not applicable to instability precipitation.

Prolonged and widespread instability precipitation is a rare event over low ground in winter and, when it does occur, is usually associated with the passage of a polar low. Therefore, ignoring for the moment the instability precipitation associated with polar lows (to which we shall return later), we can conclude that provided allowance is made for large differences of the wet-bulb lapse rate from the saturated-adiabatic, the curve shown in Figure 3, is quite effective in separating cases of rain from cases of sleet (potentially snow) during continuous moderate precipitation whose intensity is 1 mm hr^{-1} or more. It follows that when the synoptic situation is favourable for the downward penetration of snow, provided the wet-bulb lapse rate approximates to the saturated-adiabatic, snow can be expected to descend below the 2°C wet-bulb level, but is very unlikely to descend beyond the 3°C wet-bulb level.

Application to the problem of forecasting snow.—In order to make use of the curve relating T_s to I in forecasting practice it is necessary to gain some knowledge of the rate of rainfall which will be experienced over low ground during periods of prolonged frontal precipitation reaching moderate intensity at least temporarily, and associated with an air temperature near 0°C. For this purpose the rainfall tabulations of amount and duration for Mildenhall and Heathrow were examined, and occasions were noted when the following conditions were satisfied:

(1) Precipitation fell for a period of at least 6 successive hours, the duration for each hour being at least 0·8.

(2) Moderate intensity was attained (that is rainfall amount exceeded 0·5 mm) during at least one hour.

(3) Air temperature remained between 0°C and 4·5°C throughout. Using data for Heathrow for the years 1949–61, and for Mildenhall for the years 1957–61, 30 examples were found.

It can easily be shown with the aid of equation (4) of reference (9) and equation (19) of this paper that the time required for the process of cooling by melting to reduce a saturated environment with lapse rate γ_s to isothermal at 0°C when T_s has its critical value for downward penetration of snow, decreases from 2·4 hr when $I = 1$ mm hr^{-1} to 1·3 hr when $I = 4$ mm hr^{-1}. Hence if precipitation of intensity between 1 and 4 mm hr^{-1} is maintained for a period of about 2 hr,* the thawing of snowflakes during their descent has virtually ceased, and snow will be accumulating on the ground. For example if on any occasion the rainfall amount exceeded 2 mm for each of two consecutive hours, referring to Figure 3 one would expect snow to be accumulating on the ground by the end of that period provided T_s was initially 2·6°C or less.

Table I shows the result of classifying the 30 examples of prolonged precipitation according to the rainfall amount which was exceeded during each of any two successive hours:

TABLE I—

TABLE I—NUMBER OF OCCASIONS FOR WHICH HOURLY RAINFALL AMOUNT (MM) EXCEEDED STATED AMOUNT DURING EACH OF TWO CONSECUTIVE HOURS

		>0.5	>1.0	>2.0	>3.0	>4.0
Total number of occasions ..	30	29	24	8	3	0

Referring to Figure 3, these figures indicate (working to the nearest half-degree Celsius) that when periods of prolonged frontal precipitation are expected in association with a synoptic situation favourable for the downward penetration of snow, snow will very probably descend at least to the 2·0°C wet-bulb level. There is about one chance in four that it will descend below the 2·5°C wet-bulb level, and it is very unlikely to reach the 3°C wet-bulb level.

Snowfall over south-east England on 31 December 1961.—As a practical application of the curve of Figure 3 we can examine the recent and memorable example of downward penetration of snow which resulted in the heavy snowfall over south-east England on 31 December 1961, when the depth of snow exceeded 20 cm over a wide area. The prolonged precipitation was associated with a shallow frontal depression which moved east-north-east

*The duration should strictly be measured with respect to the trajectory of the air below the 0°C level, but since downward penetration of snow to low levels is almost always associated with light or moderate winds, the duration measured at a fixed point can be taken as a good estimate of the true duration.

from the Bay of Biscay across the extreme north of France to south Denmark between 0001 GMT on 31 December 1961 and 0001 GMT on 1 January 1962. The synoptic situation at 0600 GMT when rain had already changed to snow over much of south-east England (except near the east coast) is shown in Figure 6.

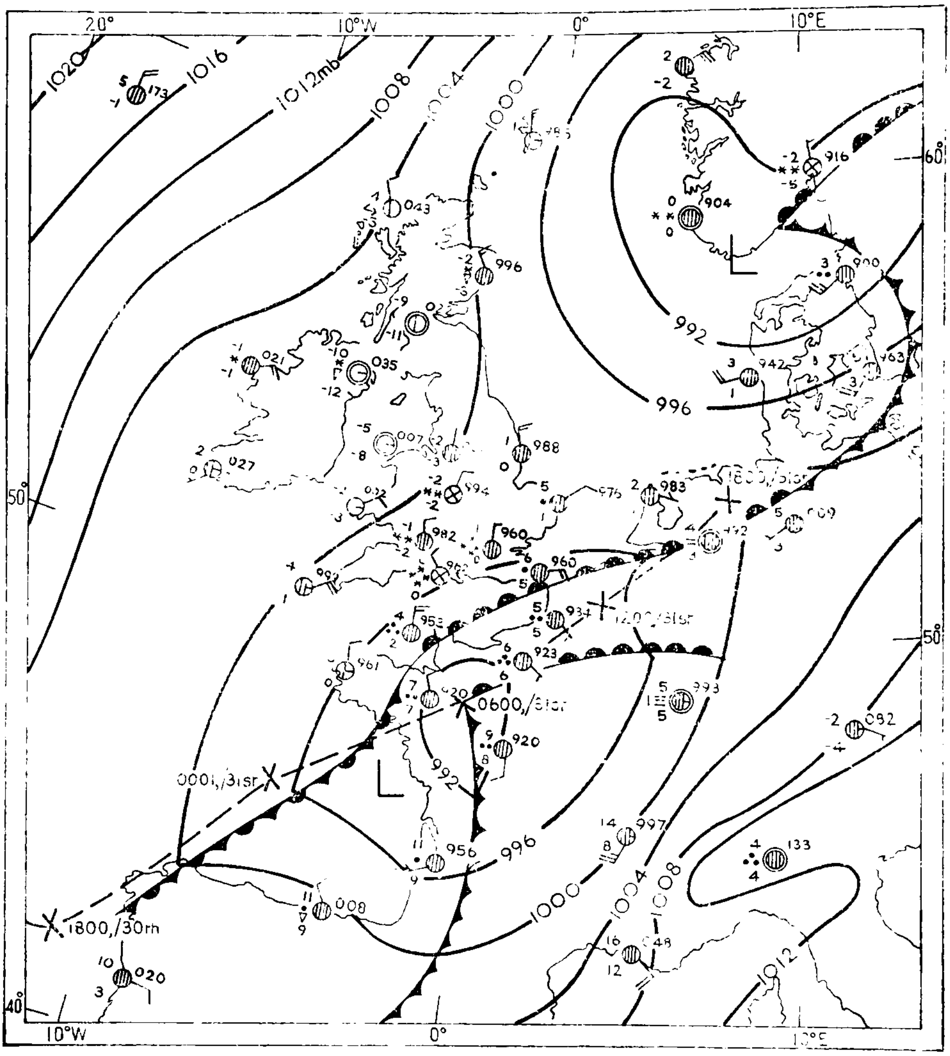

FIGURE 6—SYNOPTIC CHART FOR 0600 GMT, 31 DECEMBER 1961
— — — track of depression

The dry-bulb and dew-point curves from the surface to 850 mb at Hemsby and Crawley at 2330 GMT on 30 December 1961 are shown in Figures 7 and 8. The wet-bulb curves have been drawn by using Normand's theorem. The surface pressure at Crawley was 980 mb, but the curves can be extended almost to sea level by extrapolating to the surface dry-bulb temperature (2·5°C) and to the wet-bulb temperature (2·1°C) at Heathrow at 2344 GMT on 30 December 1961, the surface pressure being 994·7 mb.

Warmer air was present above 900 mb at Crawley but, in the absence of advection of either warmer or colder air below 900 mb, it is evident that once precipitation started, cooling by evaporation would quickly produce a lapse rate close to the saturated-adiabatic, with a sea-level wet-bulb tempera-

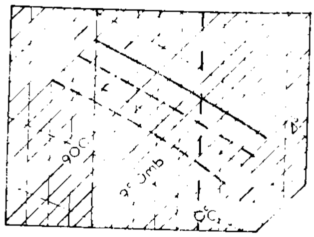

FIGURE 7—TEPHIGRAM FOR HEMSBY, 2330 GMT, 30 DECEMBER 1961
—— dry-bulb temperature
– – –– dew-point temperature
––·––·–– wet-bulb temperature

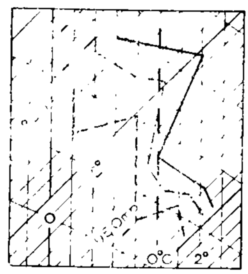

FIGURE 8—TEPHIGRAM FOR CRAWLEY, 2330 GMT, 30 DECEMBER 1961
—— dry-bulb temperature
– dew-point temperature
– · –– wet-bulb temperature
(Curves are extrapolated below 980 mb)

ture very near to 2°C. Hence given the approach of a belt of continuous precipitation exceeding 1 mm hr^{-1}, the curve of Figure 3 indicates that in the absence of advection of warmer air much of south-east England would be threatened by the downward penetration of snow to sea level. When $T_s = 2°C$, by equation (4) of reference (9) the equivalent of 2·2 mm of rain is required to cool the layer below the 0°C level to isothermal at 0°C, and allowing about one hour for saturation to be attained, snow could be expected to start accumulating on the ground not later than three hours after the time of onset of rain.

In the event, the threat of snow fully materialized. The advection of warmer air was negligible on account of the rapid movement of the depression and the very weak winds in the warm air (see Figure 6). As regards the intensity of precipitation, at Heathrow for example the mean intensity during the first three hours was the equivalent of 1·2 mm hr^{-1}, and during the next four hours was the equivalent of 2·0 mm hr^{-1}. At Heathrow rain commenced at 0205 GMT, sleet was first reported at 0357 GMT and at about 0445 GMT the screen temperature which had been falling rapidly became almost steady at 0·6°C and the recording rain-gauge became clogged with snow and ceased to function, thus indicating the time at which thawing had virtually ceased at all levels down to the ground, i.e. about 2¾ hr after the time of start of rain.

Towards 1200 GMT colder air from the north was being advected over south-east England in the rear of the depression, but the initial rapid fall of temperature towards 0°C during the first 2 to 3 hours after the onset of rain, changing the form of precipitation from rain through sleet to snow and enabling the snow to accumulate on the ground quite early in the long period of precipitation was the result of cooling by evaporation and by melting of the falling snow.

Downward penetration of snow during instability precipitation.—Some polar lows give only local showery precipitation, and these are of little importance for the problem of downward penetration of snow. The important cases are those polar lows which develop an extensive area of moderate or heavy instability precipitation. In these circumstances rain may change to snow over a wide area and the rate of accumulation on the ground may locally exceed 4 cm hr^{-1}.

In reference (1), for 27 examples of sleet or snow showers at North Atlantic Ocean Weather Stations, the author calculated the depth (D_s) below the 0°C level at which the precipitation would still have been recognizable as sleet or snow if there had been a saturated environment with a lapse rate γ_s. On all occasions, D_s was at least 500 m (corresponding to T_s = 3·0°C) and on seven occasions exceeded 700 m (corresponding to T_s = 4·2°C). By contrast, of 44 moderate or heavy rain showers which occurred during the years 1957–61 at Ocean Weather Station "Juliett" associated with a surface dry-bulb temperature of 7°C or less, on only 10 occasions was T_s (calculated by equations (9) or (10) of reference (1) as appropriate) less than 4°C and on only one occasion less than 3°C (2·9°C). Hence within an extensive area of moderate or heavy instability precipitation over the land one might expect snow usually to penetrate down to the 3°C wet-bulb level, and possibly to the 4°C wet-bulb level.

However the author does not know of any example on record for the British Isles of snow having accumulated on the ground by the processs of cooling by melting during prolonged periods of precipitation, when the surface wet-bulb temperature was initially higher than 3·5°C*. The explanation perhaps is that the snow-flakes of greatest mass in large numbers are associated with heavy instability showers rather than with the less intense but more prolonged and widespread instability precipitation which is favourable for downward penetration of snow. Hence within extensive areas of moderate or heavy instability precipitation, snow can be expected to descend to the 3·0°C wet-bulb level but is very unlikely to penetrate beyond the 3·5°C wet-bulb level. In practice, on many occasions snow will descend to sea level, since when conditions are favourable for the development of polar lows in the neighbourhood of the British Isles the sea-level wet-bulb temperature is usually less than 3·0°C.

The polar air depressions of 25–26 April 1950 and 13–14 December 1958.—It is instructive to examine what happened over south-east England during the passage of the two polar air depressions of 25–26 April 1950 and 13–14 December 1958.

On the night of 25–26 April 1950 a polar air depression moved east-south-east from the Bristol Channel to the Strait of Dover (see Figure 9). Associated with it was an extensive belt of instability precipitation which gave a period of about six hours continuous moderate or heavy precipitation at many places in south-east England, with amounts totalling around 20 mm rainfall equivalent (for example, 17 at London (Heathrow) Airport, 25 at Lympne). The upper air soundings at 2100 GMT on 25 April at Downham Market and Larkhill indicate that the wet-bulb lapse rate over south-east England was at least γ_s from the surface upwards to the 0°C wet-bulb level. The sea-level wet-bulb

*It is shown in reference (10) that the notorious Cotswolds snowfall of 1 November 1942 was not an exception to this rule.

temperature just before the onset of rain over south-east England was generally between 2·5° and 3°C, and the form of precipitation had changed from rain to snow down to sea level over a wide area within two hours of the start of continuous rain. For example at London (Heathrow) Airport rain became continuous at 2240 GMT, heavy sleet was reported at 0033 GMT, and continuous snow fell from 0110 GMT until precipitation ceased at 0435 GMT. The depth of snow lying exceeded 10 cm at many places in the counties of Surrey, Sussex and Kent.

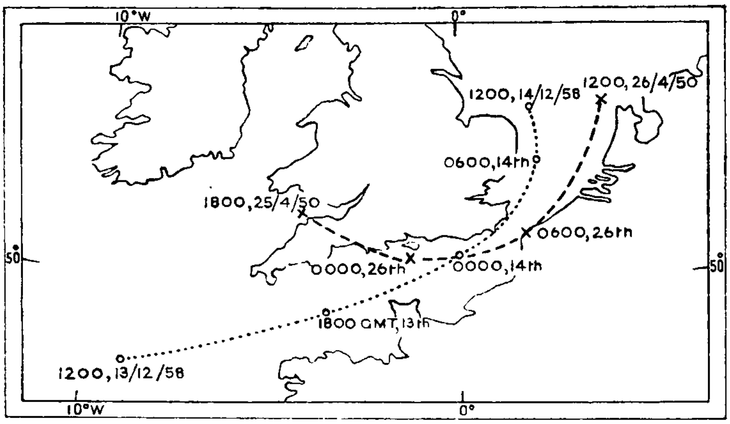

FIGURE 9 —TRACKS OF TWO POLAR LOWS

This was a straightforward example of downward penetration of snow to sea level when the surface value of T_s was initially less than 3°C.

On the night of 13–14 December 1958, a polar air depression moved up the English Channel (see Figure 9) and associated with it was a broad belt of instability precipitation which gave a period of five or six hours continuous moderate or heavy rain over south-east England, with amounts exceeding 10 mm in many places, and 20 mm locally (for example 23 mm at Heathrow). The surface wet-bulb temperature on this occasion was generally between 3 and 3·5°C and at first sight there might appear to be a serious risk of snow penetrating down to or very near to sea level. There are however no reports of precipitation changing to snow at reporting stations within the rain belt (the highest having an altitude of 157 m), and only one station reported sleet (for one observation only). The upper air sounding at Crawley at 2300 GMT on 13 December 1958 (see Figure 10) gives the explanation. Owing to the presence of an isothermal lapse rate from the surface up to 936 mb, the surface

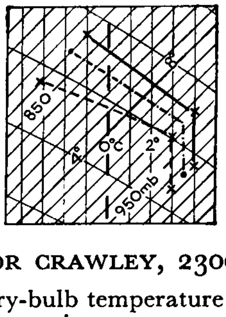

FIGURE 10—TEPHIGRAM FOR CRAWLEY, 2300 GMT, 13 DECEMBER 1958

——— dry-bulb temperature
— — — dew-point temperature
—·—· wet-bulb temperature

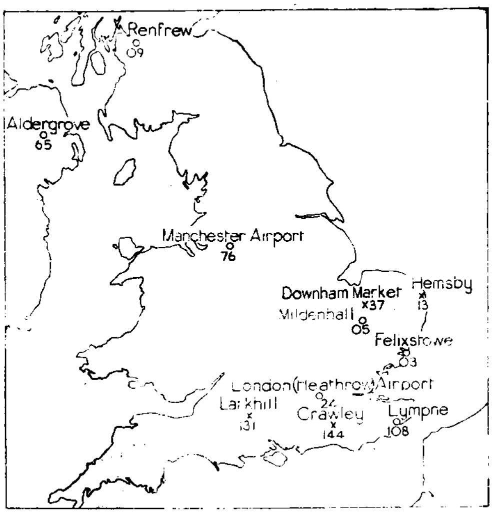

FIGURE 11—STATIONS FROM WHICH OBSERVATIONS HAVE BEEN USED
o surface observations.
x upper air observations.
The numbers indicate altitude in metres.

wet-bulb temperature of about 3·5°C was deceptive, and at all levels below 940 mb the equal-area construction gives a value of T_s higher than 3·5°C (at ground level at Crawley it was about 4·5°C). Hence snow was very unlikely to descend beyond 940 mb. Since the sea-level pressure was approximately 970 mb, it follows that snow was very unlikely to penetrate down to any ground lower than 250 m above sea level.

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551.575.36:551.591.6

SOME OBSERVATIONS OF SLANT VISIBILITY IN FOG

By J. HODKINSON

Introduction.—Although it is recognized that the visibility of objects on the ground from a few hundred feet above ground level may be very different from that observed at ground level very few measurements of slant visibility have been made. At Cardington a series of visual observations of slant visibility during fog were made during the winters of 1957–58, 1958–59 and 1959–60; some additional data were obtained by photo-electric methods during the winter of 1960–61. These observations have been examined to see whether any useful relationship between the observed values of horizontal and slant visibility could be found and also to test some theoretical relationships suggested by Stewart.[1,2] It was found that in most fogs the slant visibility is less than the horizontal visibility observed at ground level. The extent by which the slant visibility was less than the horizontal varied considerably and only very approximate relationships can be suggested.

The many factors which determine the distance at which an object or light is visible cannot be discussed at length and reference should be to a standard reference work such as the *Handbook of Meteorological Instruments*[3] or the *Handbook of Aviation Meteorology*[4]. It is, however, necessary to define briefly the terms used.

Throughout the report the term "visibility" refers to the meteorological visibility as used for observations and forecasts. It is defined as the greatest distance at which an object of specified characteristics can be seen and identified by an observer with normal eyesight against a sky horizon under normal daylight illumination. Estimates or measurements made at night are expressed in terms of the equivalent daylight visibility. The term "slant visibility" refers to the visibility, as defined above, measured along a line of sight inclined to the horizontal.

For aviation purposes the terms "visual range", "runway visual range" and "slant visual range" are often used. The visual range is the greatest distance at which a particular object or light can be seen and identified by an observer with normal eyesight under the prevailing conditions of illumination. In special conditions of illumination and/or with objects differing from the standard, the visual range may differ appreciably from the meteorological visibility; for example the visibility is worse towards the sun than away from it, particularly around sunrise and sunset. At night the visual range refers to the distance at which a given light is visible and it may be two to four times the meteorological visibility when high-powered lights are used. The runway visual range is the visual range along the runway of an aerodrome of runway lights and, in a very limited number of cases, of special marker boards. The slant visual range is the visual range along a slant path and normally refers to the slant distance at which an observer in an aircraft can distinguish lights or objects on the ground. For a given aerodrome lighting system, for which the candle powers of the lights are known, it is possible to convert the meteorological visibility into visual ranges.

Observational material.—The visual measurements of slant visibility were obtained by observing objects attached to the flying cable of a captive kite balloon which was flown at about 500 feet. The objects were attached at 5, 50, 100, 150, 200, 300, 400 and 500 feet above the ground. From the balloon anchorage a fixed base line was laid out along a level stretch of ground and markers placed at 50-yard intervals up to a distance of 800 yards. During daylight hours black beach balls about three feet in diameter were attached to the flying cable at the eight fixed heights. Observations were made by noting the horizontal distance from the balloon anchorage at which each of the beach balls was just visible; the slant visibility was readily calculated from the horizontal ranges obtained.

During the hours of darkness lights were attached to the balloon flying cable and the attenuation of these lights was measured with the aid of a Gold visibility meter. In most cases the lights were viewed from the fixed 50- or 100-yard marker on the base line, but when the visibility was good enough it was possible to use a longer base line. Readings were made with the Gold visibility meter on each light visible commencing with the lowest and working upwards to the highest visible; these readings were repeated twice to give three sets for each observation. The three sets of readings took about five to ten minutes to complete and some variation of visibility inevitably occurred during this time. The mean of the three visibility meter readings was used to calculate the equivalent daylight visibility as described in the *Handbook of Meteorological Instruments.*[3] Each observer made personal calibrations for the lights in use along a fixed base line of 100 yards and all readings were referred to these personal calibrations.

During the investigation it was hoped that, as far as possible, measurements of slant visibility could be obtained whenever the horizontal visibility fell below 800 yards, the measurements being made two or three times an hour throughout the life of the fog. The time required to set up the equipment and the restrictions inherent in operating with captive balloons (for example, wind speed and lightning risk) limited the extent to which this aim could be achieved. It was found that, with the balloon equipment used, operations were impracticable when the wind speed at flying height, normally 500 feet, exceeded 15 knots and appreciable drift occurred when the wind exceeded 10 knots at flying height. No observations were attempted during the twilight periods as the background illumination varied too widely to give reliable results. In all 248 observations were made at night and 131 by day in 45 periods of fog.

Observational errors.—It was realized that in the measurement of both slant and horizontal visibilities the observational errors might be appreciable. The main sources of error were (i) errors in the observers' estimates and (ii) errors arising from the fact that the balloon cable was not always vertical.

The errors caused by the drift of the balloon were difficult to assess as the drift was dependent not only on wind speed but also on the suspended load and the free lift of the balloon. During operations in fog these two factors varied with time mainly due to the deposition of moisture in the form of dew, hoar frost, and even on occasions clear ice. If, in the opinion of the observer, the drift was excessive the observations were discontinued or the balloon pulled down to a lower height and a curtailed set of readings made. It is estimated that under these circumstances the slant ranges may have been in error by some 10–15 per cent.

The *Handbook of Meteorological Instruments*[3] indicates that during daylight an observer's estimate of the visibility is accurate to the order of 10–15 per cent. Taking into consideration the fact that the slant range may also have been in error by a similar amount the probable error of the daylight observations was of the order of 15–20 per cent.

The estimation of the errors in the observations made at night is more complex as the function relating visibility and attenuation readings is asymetric. Variations in the brightness of the lights were reduced by stabilizing the power supply by means of a constant voltage transformer and the wiring was so designed that the brightness of each light was, as near as possible, the same. The effect of the observing errors was further reduced by using the mean of three readings to calculate the visibility instead of a single spot reading. It was estimated that the probable error in the calculated values of visibility due to observers' estimates was about 10–15 per cent. After taking into account the probable error in the slant range used for the calculations it is estimated that the slant visibilities for the night-time observations had a probable error of 25 –30 per cent.

Results.—Ideally the observations should have been equally distributed throughout the whole range of horizontal visibilities considered, but because of rapid variations it proved difficult to obtain many reliable readings with horizontal visibilities in the range 400–800 yards and the majority of the observations were made when the horizontal visibility was less than 200 yards.

Histograms were prepared showing the frequency of various values of the ratio of the observed slant visibility to the observed horizontal visibility (S_h/H) for various heights (h) and various ranges of horizontal visibility (H). Initially the observations made at night were considered separately from those made by day. It was found, however, that there were no significant differences arising from the different methods of observation and the histograms reproduced as Figure 1 are the combined frequencies derived from both day and night observations. While preparing the histograms the height of the fog top was estimated for each occasion and observations considered to have been made wholly within the fog have been distinguished from those where it was considered that the height h was above the fog top. For those observations made around the same time as the routine temperature soundings made at Cardington the height of the fog top was estimated from the sounding data. On many occasions, however, no representative sounding was available and to obtain an estimate of the height of the fog top the ratio S_h/H was plotted against h. Within the fog this plot gave a fairly smooth curve with the value of S_h/H usually, but by no means always, decreasing slowly with increasing height. It was found that on many occasions the slope of this curve changed abruptly so that S_h/H increased or increased more rapidly with height. By comparing these plots with the sounding data, where available, it was seen that the discontinuity occurred at about the height of the fog top and it was therefore considered that this provided a reasonable method of estimating the fog top when no representative sounding was available. In cases of doubt the observations were assumed to have been made wholly within the fog.

In Figure 1 the shaded areas represent the occasions where the fog top was probably not reached at the corresponding height h and the unshaded portions where it was reasonably certain that the height h was above the fog top. It is evident that within most fogs the slant visibility is usually less than the horizontal visibility and that the extent to which it is less is greater as the height increases. When the height h is above the fog top the slant visibility, as is to be expected, tends to increase markedly as h increases. The large scatter evident in the results is probably due to the difference in the size, number and distribution of the water droplets present in any particular fog.

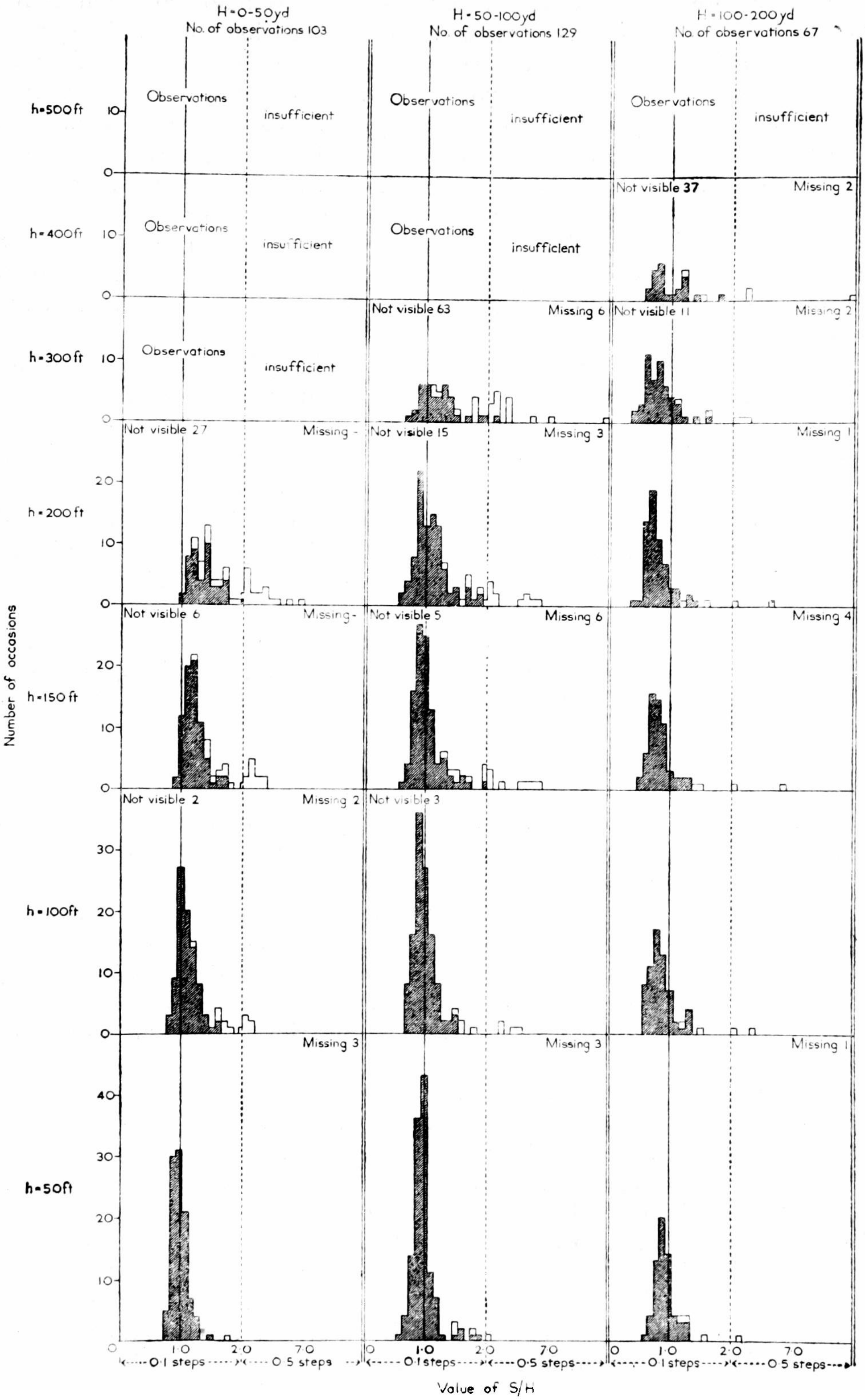

FIGURE I — HISTOGRAMS SHOWING FREQUENCY OF VARIOUS VALUES OF THE RATIO S/H

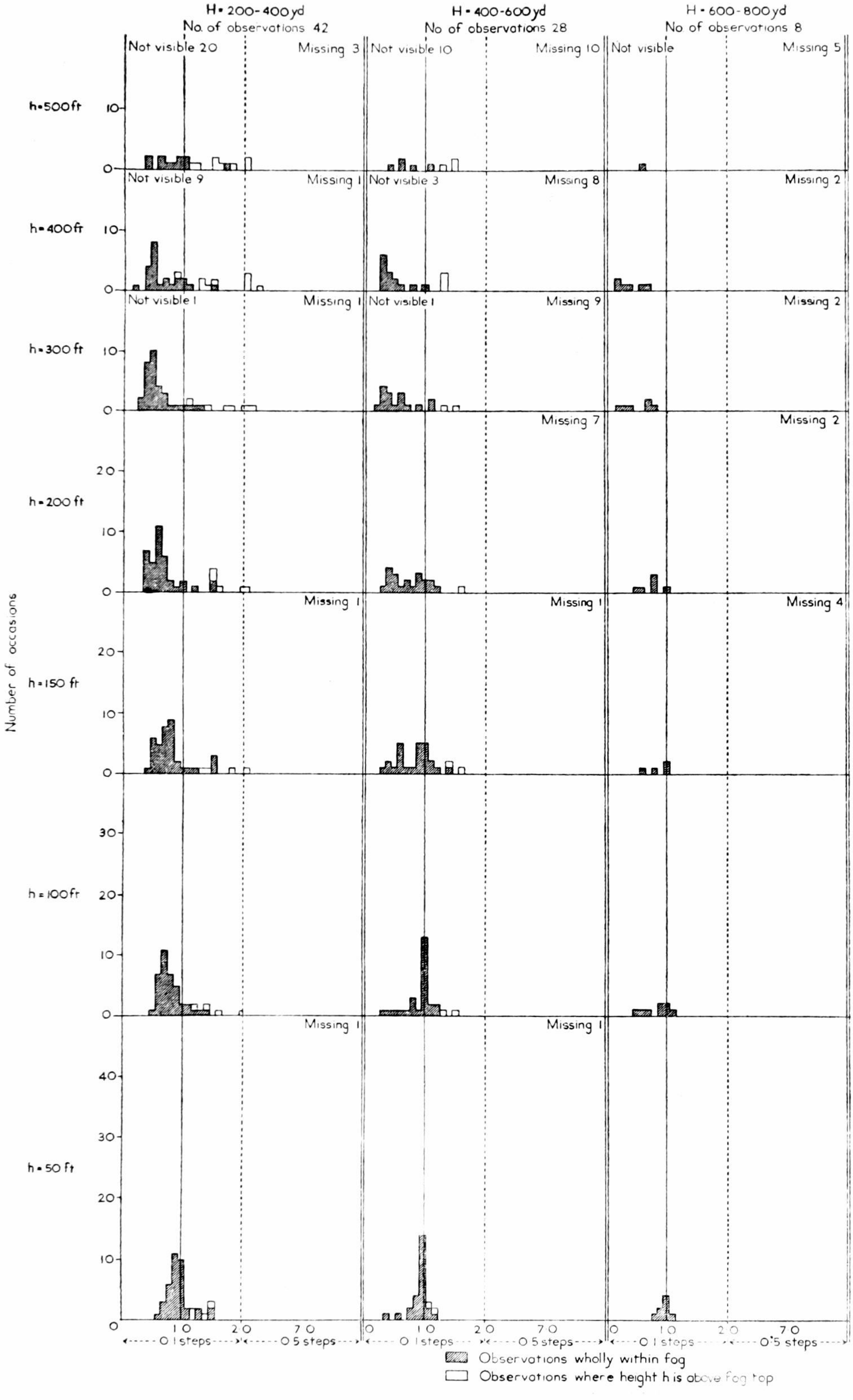

FIGURE I—*(cont.)*

In dense fogs the variation of slant visibility with height is much less noticeable. This may partly be due to the fact that it was impossible to make observations at heights of 200–300 feet when the horizontal visibility was low and the slant visibility decreased with height. The number of observations which could not be made because the object was not visible is indicated on the histograms.

In view of the risk that in dense fogs the observations may be biased towards those occasions when the slant visibility increases with height, further analysis was limited to those occasions when the horizontal visibility exceeded 40 yards when considering heights up to 200 feet, and to occasions when the horizontal visibility exceeded 100 yards when considering greater heights. The lower limit of 40 yards is about the lowest value of any practical interest to aviation with the present landing aids available. For heights of $h = 100$, 200 and 300 feet the values of slant visibility (S_h) were plotted against horizontal visibility (H) and the resulting scatter diagrams are given in Figures 2–4. The scatter of the individual observations was large and the method of least squares was

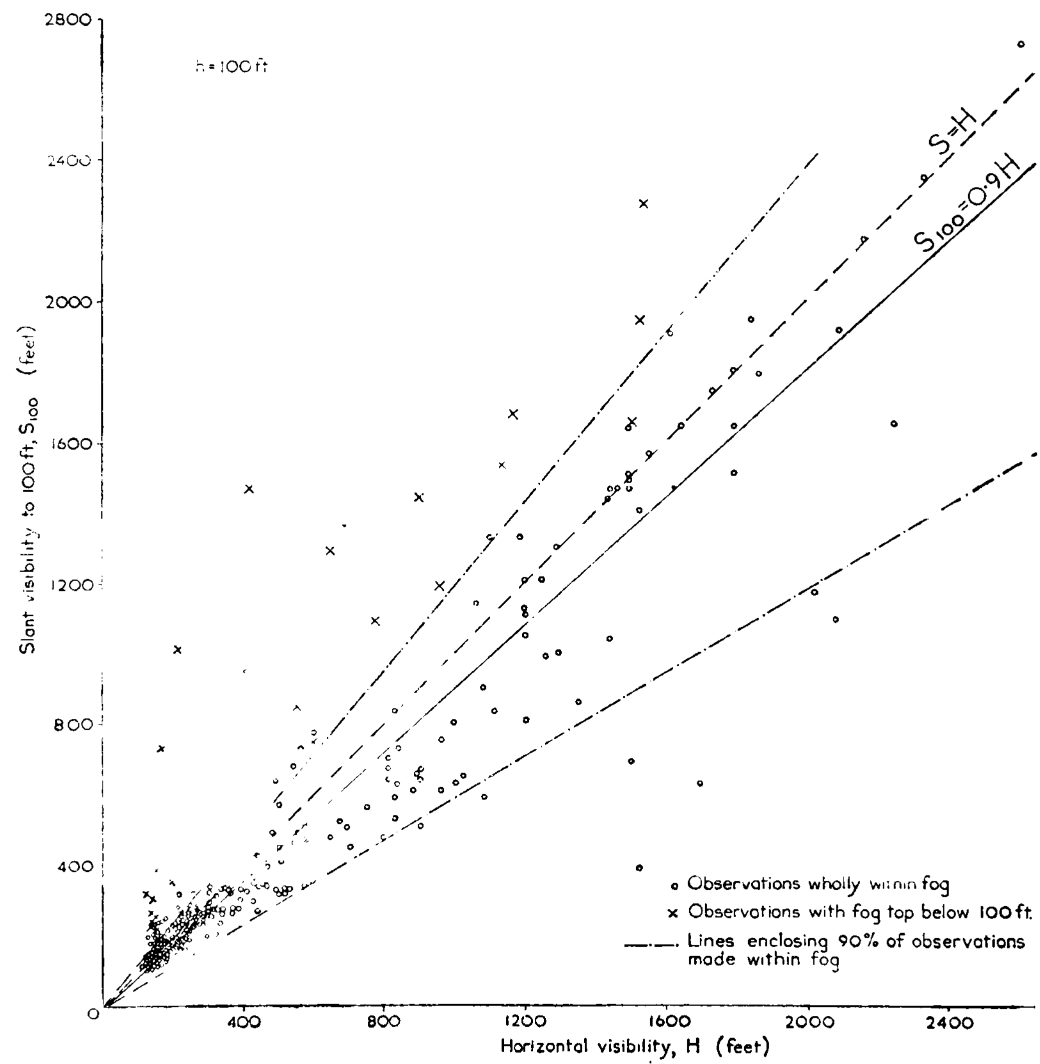

FIGURE 2 — PLOT OF SLANT VISIBILITY TO 100 FT AGAINST HORIZONTAL VISIBILITY

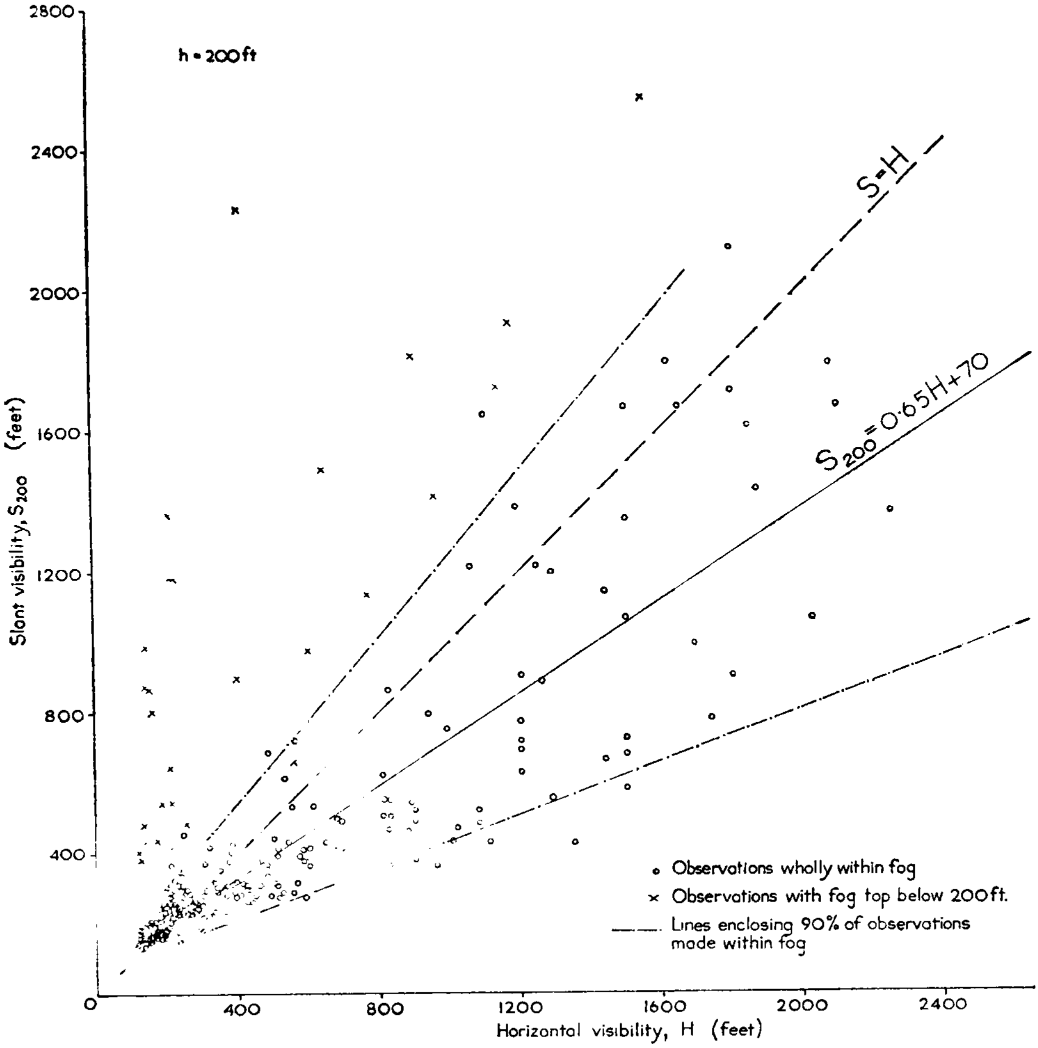

FIGURE 3 — PLOT OF SLANT VISIBILITY TO 200 FT AGAINST HORIZONTAL VISIBILITY

used to calculate a line of best fit. This has been indicated on each diagram, together with the two lines which enclose 90 per cent of all observations made wholly within the fog. It is obvious that accurate estimates of the probable slant visibility cannot be derived from these diagrams when only horizontal visibility is known. At the best it could be said that such an estimate would be better than that of slant visibility equals horizontal visibility (the only one available at present). It must be realized, however, that any such estimate might be in error by 30 per cent or more.

The approximate relationship given below, suggested by Stewart,[2] was tested.

$$\frac{S}{H} = \frac{5}{3}\,\frac{AH^{2/3}h}{(1 + AH^{2/3}h)^{5/3} - 1}$$

Where S = slant visibility,
H = horizontal visibility,
h = height of observation,
A = is a constant which depends on temperature and on the number of drops per unit volume.

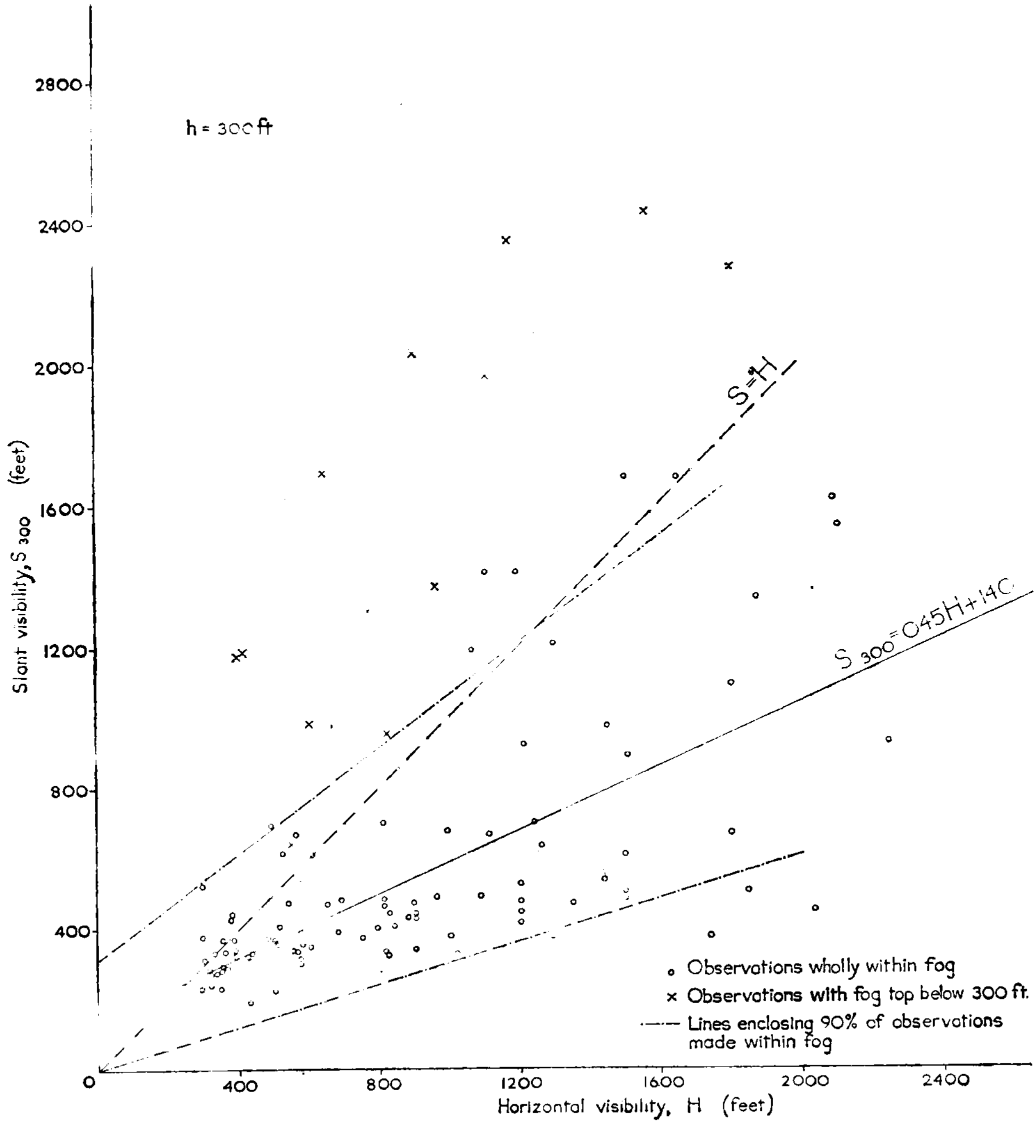

FIGURE 4 — PLOT OF SLANT VISIBILITY TO 300 FT AGAINST HORIZONTAL VISIBILITY

A number of fogs appeared to conform to a relation of this type but many did not conform at all. When the values of S derived from Stewart's suggested relationship were plotted against H using a value of $A = 1.15 \times 10^{-6}$ $(\text{ft})^{-5/2}$ it was found that the resulting curves approximately described the lower limb of the envelope containing the observations. Stewart's relationship probably represents the worst conditions which might be expected. Stewart has pointed out that it would be necessary to obtain information regarding the drop size and distribution of droplets within a fog before more accurate relationships could be formulated and the large scatter evident in the results found in this work seem to emphasize this point. It should be borne in mind that although Cardington is not seriously affected by large-scale industrial smoke pollution a local source in the form of extensive brickworks exists to the south and west of the site and on occasions the observations may have been affected by pollution from this source.

Additional data.—A scrutiny of the scatter diagrams of slant visibility against horizontal visibility shown in Figures 2–4 suggested that there might be two separate relationships linking the parameters instead of one, and as further data became available from photo-electric visibility meters set up for the main fog investigation it was decided to see whether or not there was any dual relationship, and if there was, whether it was possible to determine the type of fog in which a particular relationship held good. It was found that when the fog was deep and mature the relationship between slant and horizontal visibility is more clearly defined than that suggested by the previous work and it appears that in such fogs slant visibility is reduced to a greater extent than in the shallower less mature fogs.

The photo-electric visibility meters used at Cardington are similar to those described in the *Handbook of Meteorological Instruments*[3] and by Bibby.[5] Two photo-electric receivers are mounted on the 120 feet instrument tower at Cardington: one at the base of the tower and the other on the 120 feet platform. The two projectors are located 135 yards to the south of the tower, one being directed to each receiver. The lamps are powered from an automatic voltage stabilizer and step-down transformer with a nominal secondary voltage at 24 volts. The outputs of the photo-electric cells are measured on two adjacent channels of a Sunvic 16-channel recording potentiometer. Measurements are recorded every 80 seconds, the slant and horizontal readings being separated by a time interval of five seconds.

During the fog investigations the recorder was put into operation during the afternoon preceding a night on which fog was expected and recordings continued until the fog had cleared. The values of slant and horizontal visibility were calculated for spot readings at 10-minute intervals from the time the visibility (either slant or horizontal) approached fog limits. The visibility meters ceased to record when the visibility fell to 120 yards or below so that comparative tabulations ceased when one or other of the values fell below this figure. Subject to this limitation tabulations were completed for the whole life of the fog.

There have been objections to accepting the indications of photo-electric type visibility meters as a measure of the visibility for synoptic purposes, but these objections are not serious when comparative measurements are being made along two different paths within the same fog.

The main sources of error arise from the changes which take place in the response of the photo-cells and in the brightness of the lamps. Steady deteriorations with time were found to occur in both these factors and small changes, limited to $\pm$ 0.5 per cent, occurred in the applied voltage to the lamps. The calibration of the instrument was checked at the beginning and end of each period of fog when the visibility exceeded two nautical miles. From the changes found in the calibration over periods of 12–24 hours operation it is estimated that the errors in visibility did not exceed 10–15 per cent and on most occasions were accurate to within 10 per cent.

Results from the photo-electric visibility meters.—The raw data covered every occasion of fog for which reliable readings were available irrespective of depth, type or patchiness of the fog. The ratio S_{120}/H was calculated for each pair of observations. As the information accumulated it was evident that in some fogs the values of S_{120}/H were often in the range 0.5–0.7, and a preliminary study showed that fogs of two types gave values of S_{120}/H of this order for a large part of their life, namely:

(i) Fogs which occurred due to the lowering of low stratus cloud to ground level, the low stratus appearing before the fog.

(ii) Fogs which became deep, and in which sky conditions were reported as "sky obscured".

All fogs which fell into these two categories were used for the analysis and in all 14 out of the 25 fogs tabulated were used. Histograms were prepared showing the frequency of various values of S_{120}/H for the following ranges of horizontal visibilities: 200–400, 400–600, 600–800 and 800–1000 yards and these histograms are reproduced as Figure 5. It should be noted that when a fog fell into one or other of the two categories for an appreciable part of its life all the observations made during the whole of its life were used for the analysis and included both the development and dispersal stages of the fog. This undoubtedly accounts for some of the higher values of the ratio S_{120}/H. It is evident from Figure 5 that the scatter shown by these values is much less than that found in the previous work and given in Figure 1.

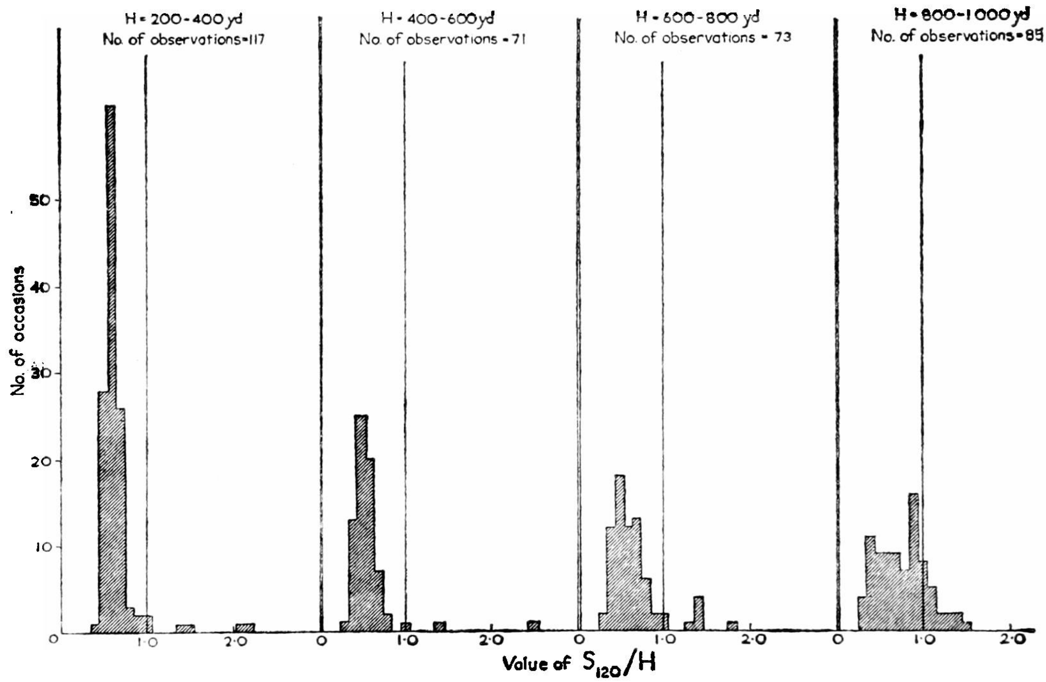

FIGURE 5 — FREQUENCY OF VARIOUS VALUES OF THE RATIO S_{120}/H IN A RESTRICTED CLASS OF FOG

The values of slant visibility used for this analysis were plotted against horizontal visibility and in order to obtain some comparison between the two methods of observation this plot was superimposed on the plot of S_{100} against H given in Figure 2 and the result is reproduced as Figure 6. It can be seen from Figure 6 that S_{120} varies approximately as 0.6 H and taking into consideration the 20-feet height difference agrees well with those observations approximating to $S_{100} = 0.7\ H$. As on the histograms, some of the plots showing a wide scatter occurred during the formative and dispersal stages of the fog.

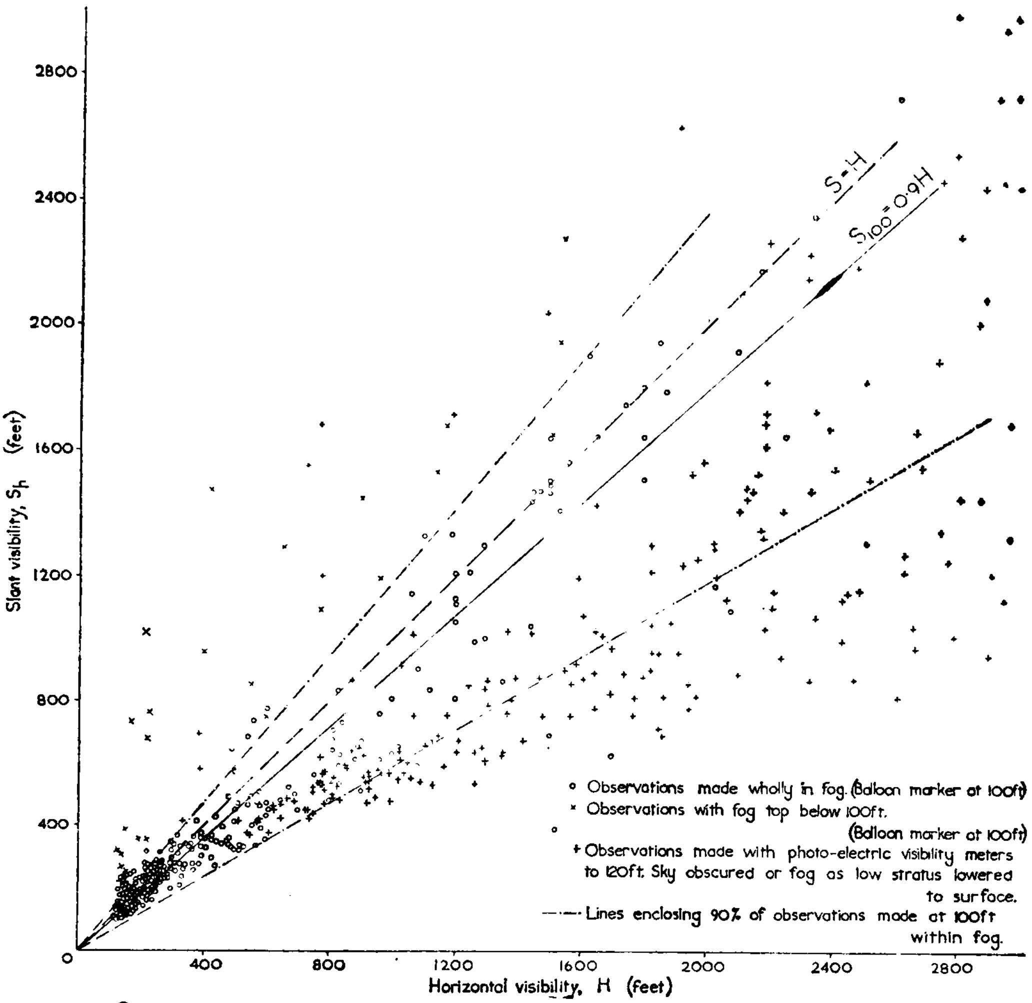

FIGURE 6 — OBSERVATIONS OF SLANT VISIBILITY MADE BY PHOTO-ELECTRIC METHODS, SUPERIMPOSED ON FIGURE 2

Conclusions.—It has been shown that within most water fogs the slant visibility is less than the horizontal visibility at ground level and that the slant visibility usually decreases with height. Statistics are given of the frequency of occurrence of various combinations of values.

The analysis of the observations of the data from the photo-electric visibility meters, although by no means an exhaustive survey, serves to indicate that in deep and mature fogs the slant visibility is reduced to greater extent than in the shallower fogs and in these mature fogs the relationship between slant and horizontal visibility may be more clearly defined.

It is evident that a more accurate knowledge of the height of the fog top is desirable as the slant visibility from above fog top is likely to be very different from that within the fog layer.

In the work carried out at Cardington it was not possible to consider the problem of large scale smoke pollution. Some measurements similar to those made at Cardington have been obtained at Kew Observatory which is more subject to smoke pollution, but the number of observations is as yet too small to warrant analysis. It would, however, appear from the observations already obtained that conditions in a smoky urban area may be different from those prevailing in a rural area free from large scale smoke pollution.

Acknowledgments.—The author gratefully acknowledges the assistance provided by the Officer Commanding, The Balloon Unit, R.A.F., Cardington, which provided the balloons and assisted with their handling. The author is also indebted to Dr. K. H. Stewart and Mr. R. H. Collingbourne of Kew Observatory for their help and guidance and also to all the Meteorological Office staff at Cardington who made the observations, often in miserably damp and freezing conditions.

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RUNWAY VISUAL RANGE, SLANT VISUAL RANGE AND METEOROLOGICAL VISIBILITY

By T. N. S. HARROWER, M.A., B.Sc.

General.—Horizontal and slant visibility in the meteorological sense are not now used by civil aircraft in the act of landing at modern aerodromes. These visibility parameters have been replaced by visual ranges which, in general, are distances at which various runway or approach lights can be seen. Depending on the intensity of these lights, visual range values are usually several times the corresponding visibilities.

It was thought that some useful results might emerge if the interesting comparisons between horizontal visibility and slant visibility obtained at Cardington[1] could be transformed into Runway Visual Range and Slant Visual Range in relation to a particular runway at Gatwick and the associated runway and approach light patterns.

Runway Visual Range and Slant Visual Range.—London (Gatwick) Airport was chosen because it was felt that the types of fog occurring there would be similar to those encountered at Cardington. An assumption was made that the transmissivity of the atmosphere as indicated by the visibilities obtained at Cardington would apply over the greater lengths of atmosphere necessary to obtain the corresponding Runway Visual Range (RVR) and Slant Visual Range (SVR). Runway 27 at Gatwick was chosen for particular examination.

Runway Visual Range is defined in the Air Navigation (General) Regulations, 1960, as "Runway Visual Range in relation to a runway or landing strip means the maximum distance in the direction of take-off or landing as the case may be, at which the runway or landing strip or the markers or lights delineating it can be seen from a point 15 feet above its centre line . . ."

Slant Visual Range in this note means the distance of the farthest approach light on the centre line which can be seen from a position on a 3° glide path.

Figure 1 shows in elevation the relationship between the runway, approach light pattern and a 3° glide path for Runway 27 at Gatwick.

The runway lights at Gatwick are raised broad-beamed lights with an effective intensity at full brilliancy of 8000-10,000 candelas. The approach light pattern extends to 2800 feet from the threshold and the approach lights have a peak beam intensity of 103,000 candelas. In azimuth from the beam centre this value drops to 50,000 candelas in $9\frac{1}{2}$° and to the same value in $1\frac{1}{2}$° in elevation. In order to allow to some extent for background brightness an average intensity of 50,000 candelas has been used for the approach lights at full brilliancy. This is certainly conservative as the central pattern from 2000 feet to 2800 feet consists of triplicate lights at each position.

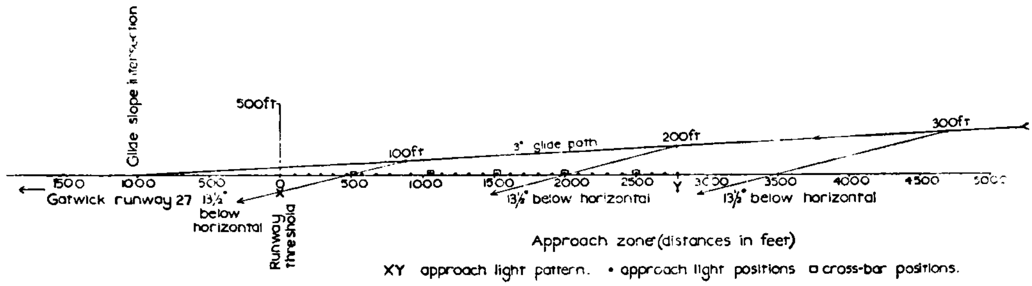

FIGURE 1 — RELATIONSHIP BETWEEN RUNWAY, APPROACH LIGHT PATTERN AND 3° GLIDE PATH FOR RUNWAY 27 AT GATWICK

In elevation beams of lights within 500 ft of runway threshold are 4° above horizontal; the beam setting in each subsequent 500 ft is increased by $\frac{1}{2}$° until between 2500 and 3000 ft from the threshold the beam of each light is $6\frac{1}{2}$° above horizontal. In azimuth the beam centres are aligned in the runway direction.

The transformation of horizontal visibility to RVR is not based on the intensity of the Gatwick runway lights but is taken from curves obtained from field experiments on the runway at Gatwick. The transformation of slant visibility to SVR is based on a conservative estimate of 50,000 candelas as the intensity of the approach lights.

Figures 2 (*a*) and 3(*a*) show the scatter diagrams obtained for $h = 300$ and $h = 200$ feet for both the runway and approach lights at full brilliancy, using the horizontal and slant visibilities obtained at Cardington. The Ministry of Aviation have stated that both runway and approach lights are operated at full brilliancy by day and night when the RVR value is below 600 yards.

These scatter diagrams apply primarily to night-time conditions and assume that the background brightness of the approach light pattern and runway lights are similar. By day, RVR is less than at night in the same meteorological visibility and so is SVR. However, as the approach light intensity is taken as some five times that of the runway lights it is felt that the ratio SVR/RVR as shown by the diagrams is probably greater by day than by night. Except in extreme conditions, such as a rising or setting sun in the line of sight, it is felt that the SVR for a given RVR by day is probably slightly greater than indicated by the diagrams. If this is accepted the diagrams can be used for both night and day cases on lights.

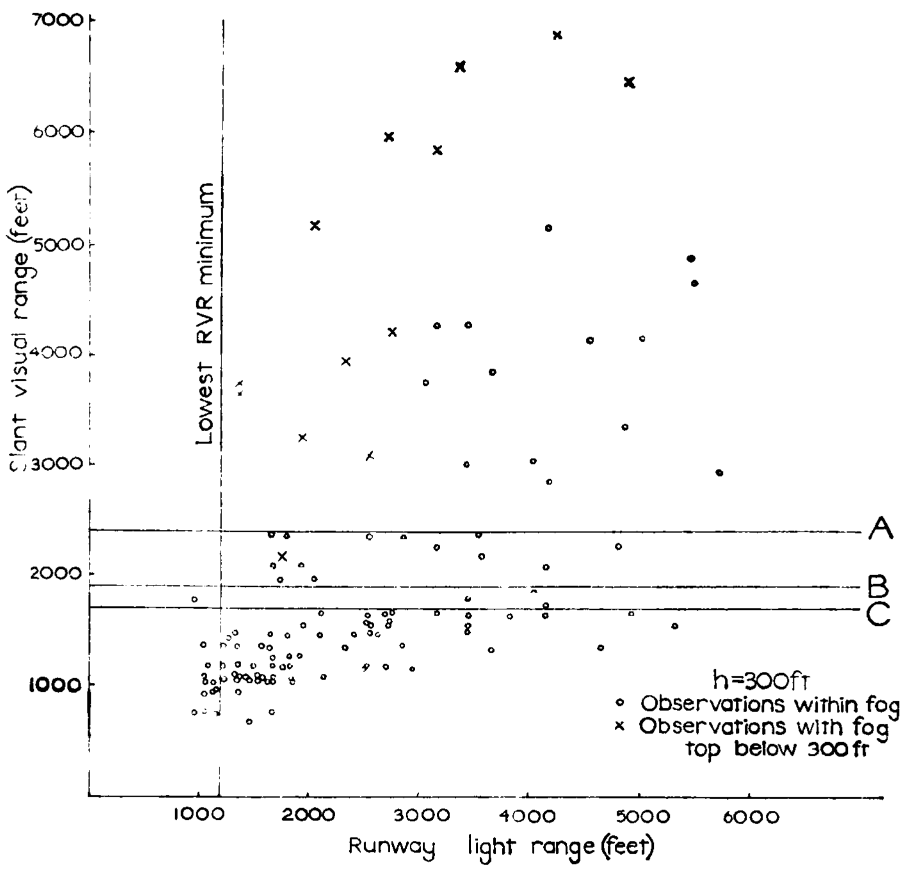

FIGURE 2 (*a*)

Some operational considerations.—The two legal minima which cover the landing of an aircraft are RVR and "Critical Height" (CH).

"Critical Height" is defined in the Air Navigation (General) Regulations (1960) as "the minimum height above the elevation of the aerodrome to which an approach to landing can safely be continued without visual reference to the ground".

The minimum values of RVR and CH are laid down by the operating company for each type of aircraft and runway and vary for each runway, aircraft type and the various types of electronic aids to landing available.

If the RVR is below minimum the aircraft must divert to another aerodrome before reaching a height equal to (CH+1000) feet.

If the RVR is above minimum the aircraft may descend to CH but can only continue the landing from CH if from that height the approach can be completed entirely by visual reference to the ground pattern or light pattern.

For Gatwick Runway 27 the lowest RVR minimum is 400 yards with an associated CH of 200 feet.

The Ministry of Aviation have given the following facts in relation to Runway 27 at Gatwick:

(i) The pilot's forward field of vision relative to fuselage datum extends to 15° down immediately ahead of the pilot, while the mean fuselage datum attitude during approach is approximately $1\frac{1}{2}$° nose-up.

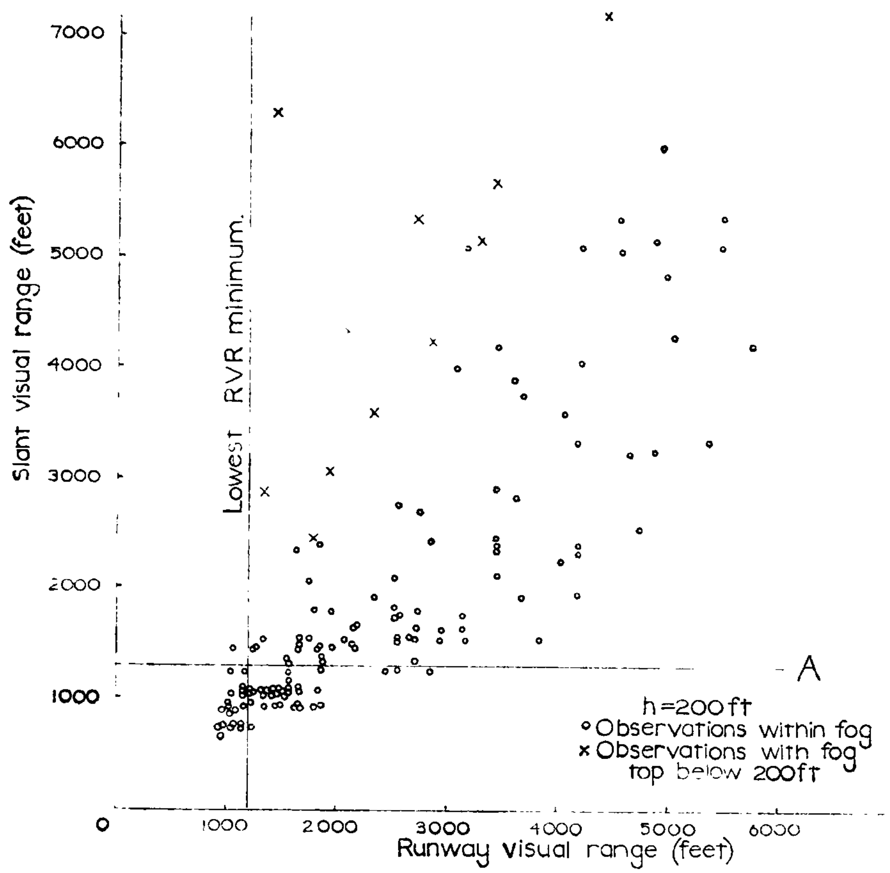

FIGURE 3 (*a*)

(ii) For adequate visual guidance the pilot should be able to see a 500 ft segment of the centre-line of approach lights.

The scatter diagram for $h = $ **300 ft.**— The limiting RVR of 400 yards is indicated by a vertical line. To see the first approach lights from 300 feet the SVR must be at least 1900 feet. This is indicated by horizontal line B on Figure 2(*a*). To obtain "adequate visual guidance" from 300 feet the SVR must be at least 2400 feet as indicated by line A.

Discussion.

(i) The area of the diagram to the left of RVR = 400 yards is not operationally important as aircraft will have diverted to an alternate.

(ii) With RVR = 400 yards or greater:

(*a*) Fog top below 300 feet (X's).—There is no case where the first approach lights were invisible. There is one case in 13 in which adequate visual guidance would not have been available.

(*b*) Fog top above 300 feet (O's).—On 71 per cent of occasions, although RVR was above limits, the first light of the approach pattern would not have been visible. On 85 per cent of occasions adequate visual guidance would not have been obtained. If, however, the approach light pattern were extended to 3500 feet from the threshold, the SVR for adequate guidance from 300 feet is 1700 feet (line C). In this case on 67 per cent of occasions adequate visual guidance would not have been obtained.

Probability curves of "adequate visual guidance" in relation to RVR for present approach pattern (curve A) and for an approach pattern to 3500 feet (curve C) are given in Figure 2(*b*).

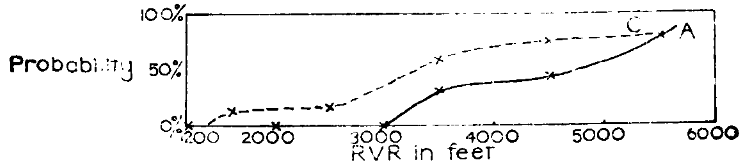

FIGURE 2(*b*)—PROBABILITY OF "ADEQUATE GUIDANCE" FROM 300 FT ON GLIDE SLOPE WHEN FOG TOP IS ABOVE 300 FT

——— A current approach light pattern (2,800 ft)

— — — C current approach light pattern (3,500 ft)

On the current approach light pattern for Gatwick Runway 27, it is interesting to note that there is no chance of adequate visual guidance at 300 feet with fog top above 300 feet unless the RVR exceeds 1000 yards.

The scatter diagram for h = 200 feet.—For adequate guidance an SVR of 1300 feet is required.

There are no cases where adequate visual guidance is not available from 200 feet if this height is above the fog top and the RVR is 400 yards or more.

When 200 feet was below the fog top, on 34 per cent of occasions adequate guidance was not available.

Probability curve for adequate visual guidance if the fog top is above 200 feet is shown at Figure 3(*b*).

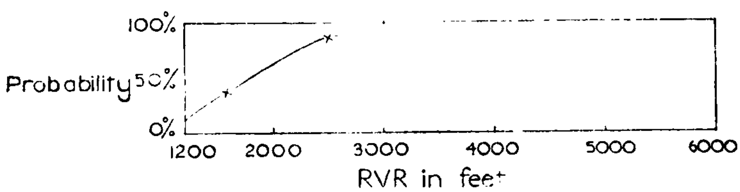

FIGURE 3(*b*)—PROBABILITY OF "ADEQUATE GUIDANCE" FROM 200 FT ON GLIDE SLOPE WHEN FOG TOP IS ABOVE 200 FT

The scatter diagram for h = 100 feet.—An RVR/SVR scatter diagram has not been constructed because it became obvious from a consideration of the visibility diagram that from 100 feet there was no case where the remainder of the approach light pattern to the threshold would not have been visible.

Conclusions.—These results can only be taken to indicate likely conditions in fogs composed primarily of water drops. They are almost certainly not representative of polluted fogs such as are found at say London (Heathrow) Airport, Manchester Airport, Birmingham Airport and other aerodromes near industrial areas.

To test these results in a practical way it would be most interesting to have statistics of the frequency of diversions by aircraft at Critical Height at Gatwick for each runway in relation to the reported RVR.

Runway Visual Range and radiation fogs.—Six radiation fogs chosen at random for London (Heathrow) Airport, London (Gatwick) Airport and Manchester Airport have been examined. The meteorological visibility throughout the history of each fog is plotted against time and shown in Figures 4, 5 and 6.

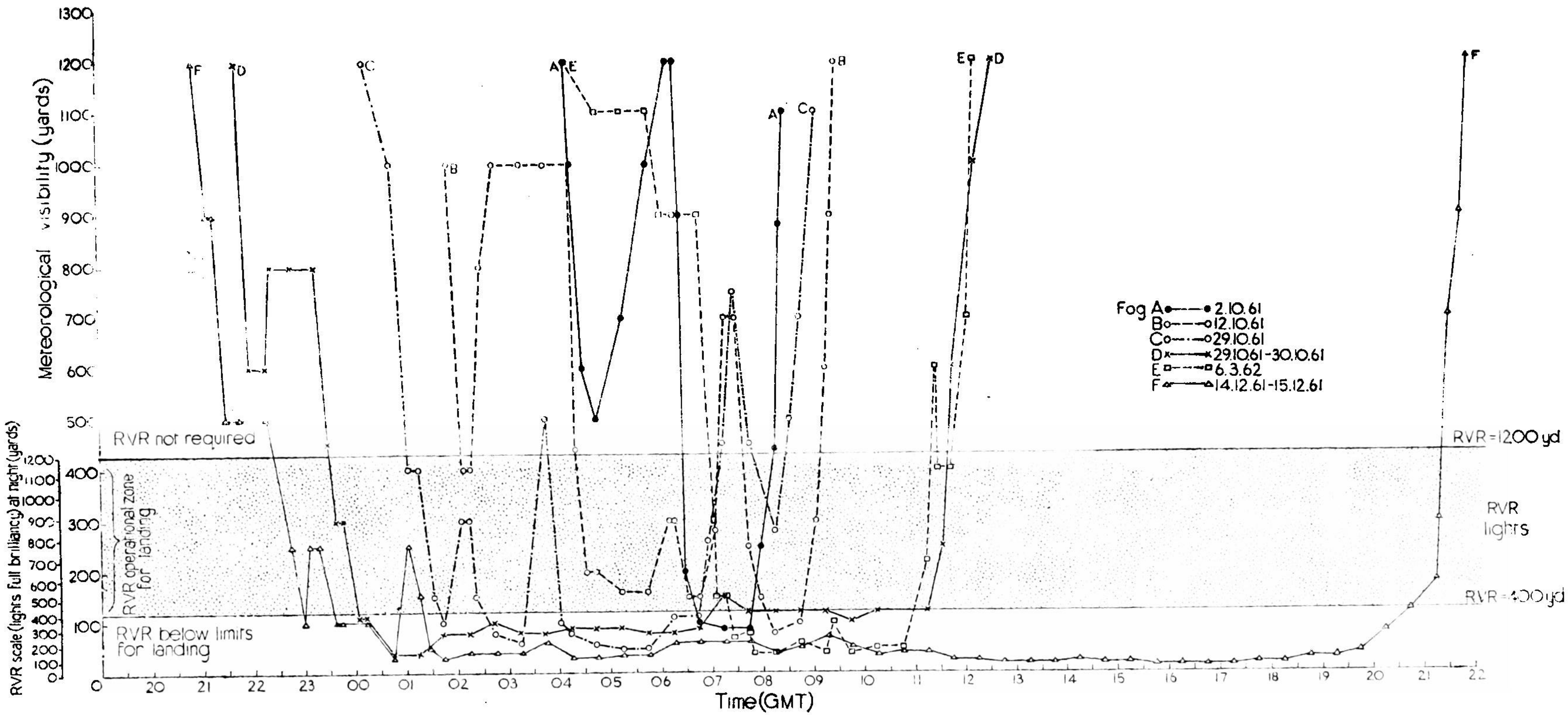

FIGURE 4 — RADIATION FOG AND RVR, LONDON (HEATHROW) AIRPORT

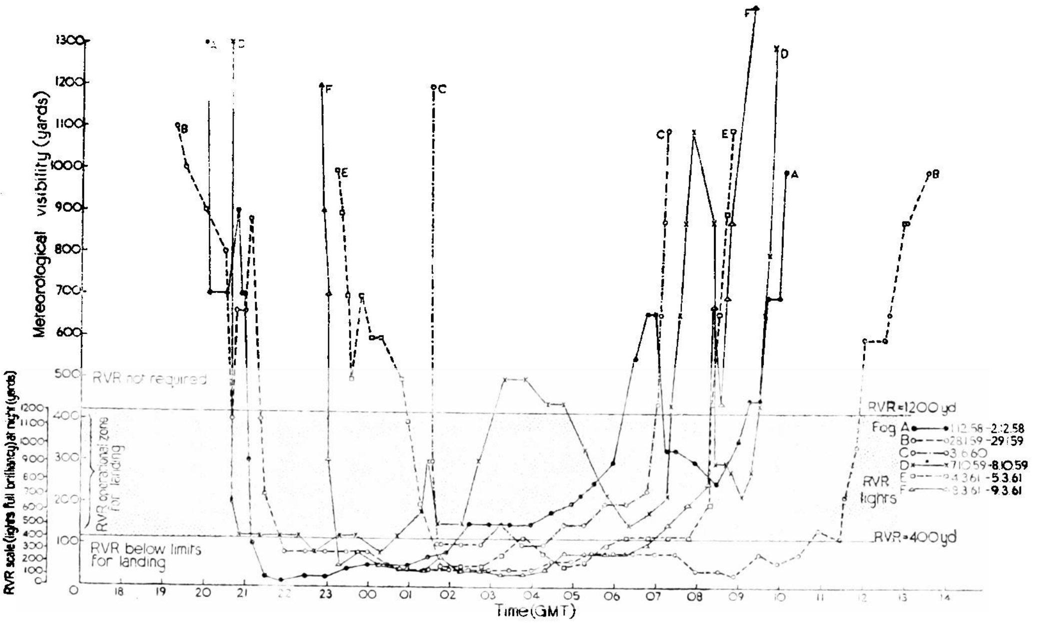

FIGURE 5 — RADIATION FOG AND RVR, LONDON (GATWICK) AIRPORT

In addition to a scale for meteorological visibility, a scale for RVR (lights at night at full brilliancy) for the particular lighting at the aerodrome concerned has been included. The RVR "operational zone for landing" from 400 yards to 1200 yards has been indicated.

London (Heathrow) Airport.—Of the six fogs considered, only two, fogs D and F, did not show considerable variations in RVR throughout the life of the fog. In the mature and thick period RVR was generally in the range 100–400 yards.

Some rates of variation of RVR within the RVR range 1200–400 yards have been computed. In six cases of falling RVR the rates of fall were 20, 23, 24, 32, 53 and 57 yards min^{-1}. In seven cases of rising RVR the rates of rise were 21, 30, 32, 33, 35, 36 and 40 yards min^{-1}. In these six fogs the highest rate of fall occurred in fog C at about 0400 GMT at 57 yards min^{-1}.

London (Gatwick) Airport.—It is likely that radiation fogs at Gatwick are "cleaner" than Heathrow fogs. Again Figure 5 indicates that there is no standard pattern for a radiation fog and that large variations in visibility with time can take place during the period of fog thickening, dispersing and even during the middle period of the fog's life.

The rate of change of RVR within the operational landing range were computed and for falls were 21, 27, 67, 67, 100 and 140 yards min^{-1}, and for rises 5, 10, 12, 12, 30 and 30 yards min^{-1}. It will be noted that the rates of fall for the "country" fogs at Gatwick can be much higher than for those of Heathrow but the rates of clearance are lower at Gatwick.

Manchester Airport.—The fogs examined for Manchester Airport show a wide variation (Figure 6). Rates of fall of RVR within the operational landing range were 5, 8, 13, 20, 22, 24, 44, 60, 87, 90 and 100 yards min^{-1} and rates of rise were 3, 11, 13, 24, 30, 30, 40, 40, 47 and 57 yards min^{-1}.

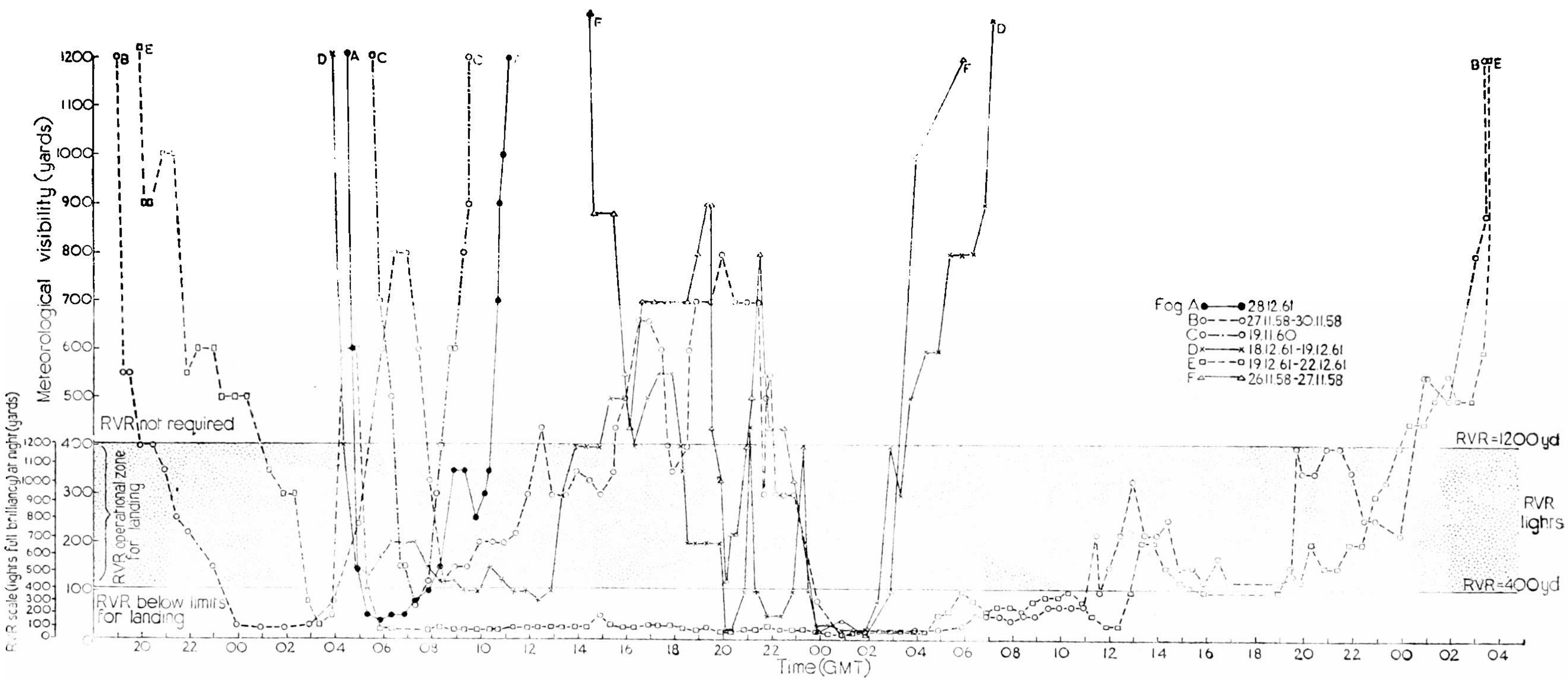

FIGURE 6 — RADIATION FOG AND RVR, MANCHESTER AIRPORT

From the operational point of view, rapid falls during fog thickening emphasize the extreme importance of accurate RVR observations reaching the pilot with the minimum delay possible. It does not appear to be so vital to get RVR observations to the aircraft so quickly when the fog is clearing, but even then great care must be exercised, as in some cases a fog appears to be clearing but subsequently thickens again.

Acknowledgment.—The use of data to give the probability diagrams shown in Figures 2(*b*) and 3(*b*) was first suggested by Mr. E. S. Calvert, O.B.E., of the Royal Aircraft Establishment at Farnborough.

REFERENCE

1. HODKINSON, J.; Some observations of slant visibility in fog. *Met. Mag., London,* **92**, 1963, p. 15.

AWARDS

L. G. Groves Memorial Prizes and Awards

The presentation of the L. G. Groves Memorial Prizes and Awards for 1962 took place in the Air Historic Room at Air Ministry, Whitehall, on 2 November 1962. The prizes were presented by Major K. J. Groves at a ceremony presided over by the Deputy Chief of the Air Staff, Air Marshal Sir Ronald Lees, and attended by the Director-General of the Meteorological Office, Sir Graham Sutton.

There were three awards. The Flight Safety Memorial Prize was awarded to *Sergeant P. N. Kirwan,* ground radar fitter, the Meteorological Memorial Prize to *Mr. C. E. Wallington,* of the Meteorological Office, while the Meteorological Observer's Memorial Award was presented to *Flight Lieutenant K. Ignatowski* of No. 202 Squadron, R.A.F., Aldergrove.

In his opening remarks, Air Marshal Sir Ronald Lees emphasized how grateful the Air Ministry were to be able to make these annual awards. They served a useful and most practical purpose in encouraging constructive work and stimulating foreseeing, practical thinking, leading to a greater reliability and safety in flying. Major Groves, before presenting the prizes, said that he believed the purpose of the awards had been fulfilled. A total of 46 prizes had been awarded since they were instituted in 1945. He felt privileged to be able to give them and so help towards the goal of making flying safe.

The Air Meteorological Observer's Memorial Award was then received by Flight Lieutenant K. Ignatowski. A Hastings captain engaged on meteorological reconnaissance duties, he had completed 2500 hours of flying. His award, a colour-slide projector, was granted in recognition of his meritorious service in this field.

The Meteorological Memorial Prize, a typewriter, was given to Mr. C. E. Wallington, Principal Scientific Officer in the Meteorological Office, for his research on the application of computers to weather forecasting and for his presentation of scientific information about the atmosphere and meteorology in a simple and graphic manner, in lectures, articles and by personal contact.

Finally, the Flight Safety Memorial Prize, a wrist-watch was presented to Sergeant P. N. Kirwan for designing a modification which can be fitted to existing and future ground radar installations, whereby distress signals from operational R.A.F. aircraft fitted with special equipment may now be more readily identified.

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PRESENTATION OF L. G. GROVES MEMORIAL PRIZES AND AWARDS.

(see p. 34)

Left to right: Flight Lieutenant K. Ignatowski, Mr. C. E. Wallington, Sergeant P. N. Kirwan.

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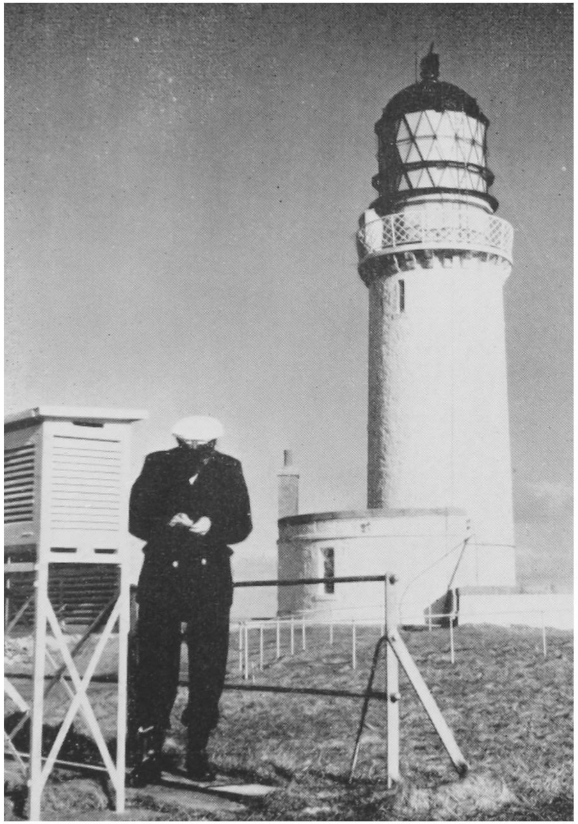
PRESENTATION OF L. G. GROVES MEMORIAL PRIZES AND AWARDS.

(see p. 34)

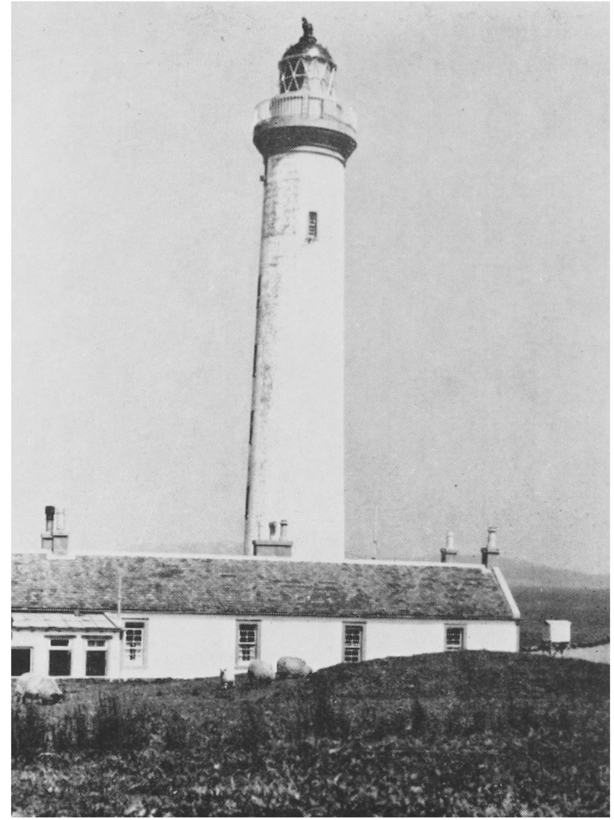
Left to right: Air Marshal Sir Ronald Lees, Mr. C. E. Wallington, Major and Mrs. K. J. Groves, Flight Lieutenant K. Ignatowski, Sergeant P. N. Kirwan.



Photograph by D. J. George

LIGHTHOUSE AT CAPE WRATH

In this photograph the temperature readings are being taken by Keeper J. Budge. See also photograph and caption opposite page 2.



LIGHTHOUSE AT RHUVAAL, ISLAY, LOOKING NORTH-EAST

The station was built in 1859 on the northern tip of Islay, and is accessible by boat from Port Askaig. It has been an auxiliary meteorological station (reporting three-hourly) since 1957. The light was converted to electric operation in 1960, and is 84,000 candle-power and visible to ships up to 18 miles away.

LETTERS TO THE EDITOR

Thunderstorms and tornadoes

It is interesting to note that the pattern of thunderstorm distribution in "Thunderstorms in Great Britain" by Starrett and Miller (*Meteorological Magazine*, September 1962) is very different from that shown by C. E. P. Brooks in *English Climate* (English Universities Press Ltd., 1954).

The preferred strip of coast between Hastings and Eastbourne is strange. Perhaps thunderstorms drifting across the Channel have preferred courses. No doubt the westward extension inland is connected with the North Downs: the convective activity in this area has been familiar to me for nearly 50 years first from Hastings, and now from here. It is often marked by a line of towering Cu passing into Cb.

Regarding tornadoes in this country there may have been an earlier example, in 1626, as indicated in the following extract from *A Mirror of Witches*, by Christina Hole, Chatto and Windus, 1957.

> "About this time (June 12 1626) there happened at three o'clock in the afternoon a terrible storm of rain and hail in and about the City of London, and with it a very great thunder and lightning. The graves were laid open in St. Andrew's Churchyard in Holborn by the fall of the wall which brought away the earth with it... At the same instant of time there was a terrible storm and strange spectacle upon Thames by the turbulency of the waters, and a mist that arose out of the same, which appeared in a round circle of a good bigness above the waters . . . And at last this round circle (thus elevated all this while above the water) dispersed itself by degrees like the smoke issuing out of a furnace, and ascended higher and higher till it quite vanished away . . . The Parliament was then sitting and this spectacle was seen by many of the Members out of the windows of the House."

2 Park Road, Tunbridge Wells, Kent. CICELY M. BOTLEY

Reply from Major Starrett:

"Our experience in climatology, both here and in England, leads us to expect analyses to vary markedly. In 1950, I very carefully analysed 30 years of tornado records for the United States. The following year, so many tornadoes occurred in one of my well-established minima, they practically eliminated it. By the erratic nature of thunderstorms and tornadoes, climatological patterns must be considered approximate at best.

"The very interesting storm of 12 June 1626 reminds us that tornadoes and waterspouts are older than history, and we are glad to have this account brought to our notice."

New Mexico, U.S.A

METEOROLOGICAL OFFICE NEWS

Cross-country race at Manchester.—A cross-country race was held at Manchester Airport on 29 September 1962. The race, which was organized by Mr. G. M. Band, meteorological officer in charge, was held over a 4-mile course round the airfield, and seven teams comprising 37 runners of all ages from various airport departments took part. The Fire Section won the event, Air Traffic Control were second, and the Meteorological Office came third. Prizes, including a cup for the winning team, to be held for a year, were presented by the Chairman of the Manchester Corporation Airport Committee.