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FORECASTING GRASS MINIMUM AND SOIL TEMPERATURES UNDER CLEAR SKIES AND LIGHT WINDS

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Summary.—An assessment is made of the relative importance of the influence of air and soil moisture, and air and soil temperature on grass minimum temperature. It is considered that under radiation conditions (that is, under clear or fairly clear skies and light winds) when minimum temperatures are liable to be lower than normal, more accurate forecasts of grass minimum temperature could be obtained by using both soil and air data than by using air data only. Some forecasting methods, using both soil and air data, are examined. The forecasting of soil temperatures is also considered.

Introduction.—The general equation of heat conductivity in soil may be written

$$\frac{\partial \theta}{\partial t} = a\left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2}\right),$$

where θ is the temperature at a point with co-ordinates x, y, z at time t, and a depends on the conditions of the soil. Assuming no horizontal flow of heat, that is, the soil is homogeneous in a horizontal plane, then

$$\frac{\partial \theta}{\partial t} = a\frac{\partial^2 \theta}{\partial z^2}, \qquad \ldots\ldots (1)$$

where θ is now the temperature at depth z and time t; a is the diffusivity $k/c\rho$, where k is the heat or thermal conductivity of the soil, c is the specific heat and ρ its apparent density.

The temperature of the surface of the earth during a spell of clear weather may be represented to any desired degree of accuracy by a finite number of terms of a Fourier Series. In clear summer weather, it appears that the surface diurnal variation can be closely approximated by a single sine term,[1] and the solution to equation (1) may then be written

$$\theta = \theta_0\, e^{-z\sqrt{\frac{\pi}{aT}}} \sin\left(\frac{2\pi}{T}t - z\sqrt{\frac{\pi}{aT}}\right).$$

θ may be regarded as a deviation from a daily mean temperature, which at the surface is θ_0, and time t as measured from the time of this surface temperature θ_0.

Sin x assumes maximum values for even (or zero) values of r and minimum values for odd values of r, where x equals $(2r+1)\ \pi/2$. Thus maximum and minimum values of θ occur when

$$t = z\left(\sqrt{\frac{T}{4\pi a}}\right) + \frac{T}{4} + \frac{rT}{2},$$

where r (odd) corresponds to minimum values of θ

and r (even or zero) corresponds to maximum values of θ.

That is, t (hours) $= 1\cdot38z/\sqrt{a} + 6 + 12r$,

which gives a surface minimum temperature at $t = 18$ hours (measured from the time of the daily mean temperature), and a lag of $1\cdot38z/\sqrt{a}$ hours in the daily temperature at depth z centimetres, for example, lags of $2m$ and $4m$ hours approximately, at a depth of $10m$ centimetres, for diffusivities of 0·0125 and 0·003 (cm. sec. units) respectively.

Substituting certain values for diffusivity and time, for example, $a = 0\cdot0125 \times 60^2$, $t = 20$, 21 or 22 (that is, 2, 3 or 4 hours respectively, after the time of the minimum surface temperature), the calculated values of θ are approximately linear with depth between four inches and one to two feet. This means that these values of θ and z roughly satisfy the equation

$$a\frac{\partial^2\theta}{\partial z^2} = 0,$$

which is the equation corresponding to "steady state" conditions.

In an investigation into the use of soil data for forecasting night grass minimum temperatures under radiation conditions, with special emphasis on spring frosts, some April and May data were examined. The 0900 G.M.T. temperatures at Rothamsted (recorded at 4 inches, 8 inches, 1 foot and 2 feet under bare soil and 4 feet under grass) following strong radiation nights were plotted and it was found that generally between 4 inches and 1 to 2 feet, the "linearity" condition was roughly satisfied but that from 2 feet to 4 feet there was a substantial decrease in the soil lapse rate. The value of the approximately constant lapse rate in the top soil varied from occasion to occasion, as might be expected with the varying conditions of soil moisture, etc.

It might be expected that the "linear" condition would extend to the surface if for the surface temperature a night minimum surface temperature (G_0, say) were used. Hence we might expect that, for a given depth z, $(\theta_z - G_0)$ would be constant for given soil conditions, following radiation nights, at least for some particular time of the year. If G be the night *grass* minimum temperature, $(\theta_z - G)$ ($= \varphi_z$, say) would be constant, if we could assume also that for given soil conditions, etc., the mean lapse rate from the surface of the ground to the grass top is constant and that the height of the grass is standard. The constancy of φ_z for given soil conditions, etc., is assumed in some of the methods of forecasting grass minimum temperatures examined below.

Data.—The data used refer to Rothamsted, a station situated at 51°48′N., 00°22′W., height 420 feet, at the top of a slight rise, on clay soil. Wind data however were recorded by an anemometer with a mast 35 feet high, on a building 35 feet high, on ground 450 feet above mean sea level. There is no obstruction to free drainage of cold air and there are no sheets of water in the vicinity. The period under study covered the ten years 1941–1950 inclusive. During this period some 60 to 70 occasions (during April and May) were selected for special study. The days selected were those on which Rothamsted was in a ridge of high pressure or anticyclone during the night concerned and when there was well broken or no cloud. From these occasions a further set of "radiation" nights were selected. This selection (17 occasions in April and 30 in May) were those days on which the run of night wind was less than five miles and consisted mainly of ground state 0B (surface of ground dry) and nothing higher than 1A (surface of ground wet), that is, including 0A (dried out, sun-baked or cracked soil) and 0C (surface of ground not wet but dew or wet grass).

All soil and grass minimum temperatures refer to readings at 0900 G.M.T. at Rothamsted. Sunshine and rainfall values also refer to Rothamsted records. Some use was made of afternoon dry-bulb and dew-point temperatures at Dunstable, as these data are not available for Rothamsted.

Changes in 0900 G.M.T. soil temperature in 24 hours.—For the selected "radiation" occasions the change, in degrees Fahrenheit, in the soil temperature during the 24 hours from 0900 to 0900 (Y) is regarded as positive when temperature rises. The value of Y was considered for two levels, z equal to 4 inches and z equal to 10 inches (regarded as the mean of 8 and 12 inches). For each of these "depths", the value of Y was plotted against the number of hours of sunshine (S) during the day in question and separate graphs were constructed for each of the months April and May. Against each point the run of wind (x, in miles) from dawn to dusk was plotted. In each case the best line to fit the points was estimated visually. The lines appeared roughly to fit the formulae

$$Y = (S - N/2 - 3)\ \tfrac{1}{2} \sin \phi \text{ for mean of 8 and 12 in.}$$

$$\text{and } Y = (S - N/2 - 1)\ \tfrac{1}{2} \sin \phi \text{ for 4 in.,}$$

where ϕ = angle of maximum elevation of sun

($\sin^{-1} 0{\cdot}74$ and $\sin^{-1} 0{\cdot}86$ for mid-April and mid-May respectively)

and N = length of night in hours

(about 10 and 8 for mid-April and mid-May respectively).

It was seen from the graphs of Y against S that when x is large the value of Y, for a given value of S, tends to be over-estimated by the formula and that when x is very small the value of Y tends to be under-estimated. It thus appears that the formula holds reasonably well for rather "average" wind runs but that for more extreme values a correction should be applied to S. For each month (April and May) and for each of the two "depths", a graph was drawn, in which the abscissa was the run of wind (x) and the ordinate was the ratio S'/S, where S' is the value of S adjusted to give the correct value of Y using the formula above. Thus for each month, a "correction" curve was obtained for each depth (see Fig. 1). For each occasion, using the values of S and x, we can obtain a "corrected" or "weighted" S or "equivalent" sunshine S'.

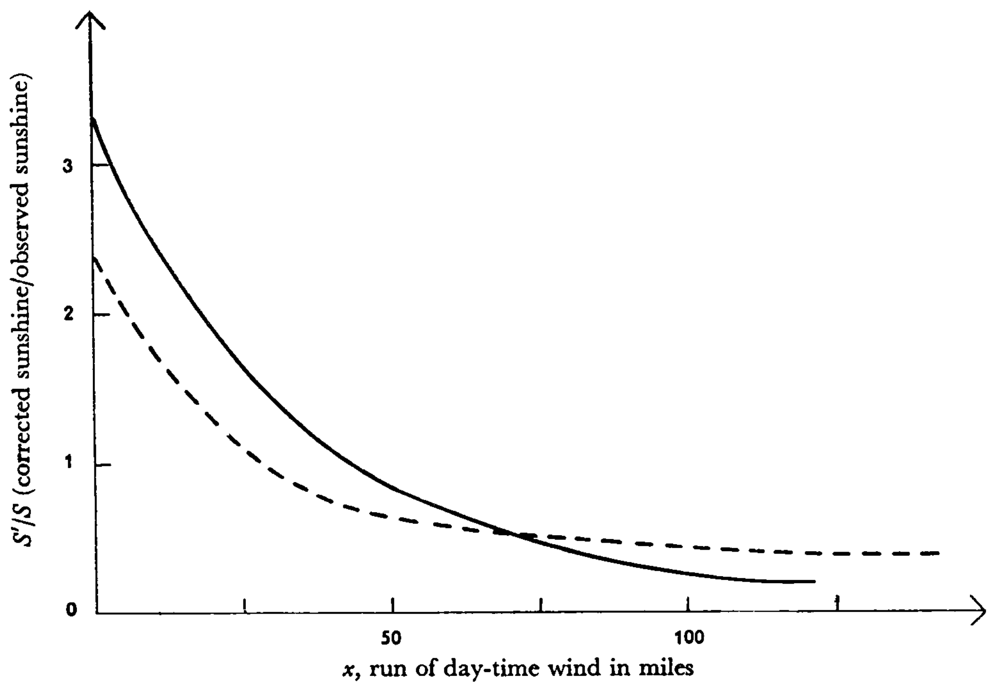


FIGURE I—THE EFFECT OF WIND ON THE WARMING OF SOIL BY SUNSHINE

— April ---May

Thus $Y = (S' - N/2-3)\ \frac{1}{2} \sin \phi$ for depth 8 to 12 in.

and $Y = (S' - N/2-1)\ \frac{1}{2} \sin \phi$ for depth 4 in.

Using these formulae and the equivalent sunshine (S') as obtained from Fig. 1 and ignoring amounts of S' in excess of eleven hours, the errors in Y are as shown in Table I. The last column in this table shows the magnitude of errors obtained using the statistical formula, $\theta = \theta_m + \rho(\theta' - \theta_m)$, where θ' and θ are the soil temperatures on consecutive days (at 0900), that is, before and after the 24-hour period, θ_m is the long-term average value of θ (for selected "radiation" nights in April and May respectively) and ρ is the correlation coefficient between θ and θ'.

TABLE I—ERRORS (°F.) IN FORECASTING SOIL TEMPERATURES 24 HOURS AHEAD, BASED ON SUNSHINE AND WIND ONLY

	Physical Method			Statistical Method*		
	Mean error	Mean absolute error	Standard deviation of error	Mean error	Mean absolute error	Standard deviation of error
April, 4 in. (17 occasions)	+0·08	1·21	1·45	+0·09	1·55	1·81
May, 4 in. (30 occasions)	−0·08	1·04	1·50	+0·65	1·70	1·94
April, mean of 8 and 12 in. (17 occasions)	+0·15	0·56	0·72	−0·02	1·19	1·44
May, mean of 8 and 12 in. (30 occasions)	+0·01	0·84	1·15	+0·33	1·44	1·74

* Using formula $\theta = \theta_m + \rho(\theta' - \theta_m)$, where θ' is the soil temperature 24 hr. before the temperature θ is recorded, and ρ is the correlation coefficient between θ and θ' on "radiation" nights.

Forecasts of soil temperature for 24 hours ahead, at least at 4 inches, could probably be improved by considering also the other important air and soil variables.

The Y–S graphs described above illustrate that wind reduces the soil-warming power of sunshine; the weighting factors (for soil temperatures at 8 to 12 inches) are given by the curves of Fig. 1. It is of interest to note that during May (see Fig. 1), it appears that wind does not "reduce" the warming effect of sunshine as much as it does in April. This could be due to the fact that the mean (nearest) sea temperature in May (52°F.) is five degrees warmer than in April, so that in May, air streams are on the average warmer and have a higher water content. This suggests that the "source" or "air-mass" classification (for example, Belasco's[2] classification) may serve as a useful guide for forecasting of both soil and grass minimum temperatures.

Forecasting grass minimum temperatures.—For the forecasting of ground frost on radiation nights in Münster (a lowland station), Faust[3] proposed the formula

$$G < 32 \text{ when } T + E/2 \ (= H, \text{say}) < 79,$$

where T and E are screen dry-bulb temperature and dew-point respectively, in degrees Fahrenheit at 1400 local time. It is also specified that cloud should be less than 2 tenths and wind speed less than Beaufort force 2 during the cooling period. No allowance is made for possible advection of different air after 1400 hr. Jefferson[4] applied the formula to Hullavington in Wiltshire and found the "constant" to be 79. Hullavington (321 feet, loam over clay) is generally flat in the immediate vicinity but with an extremely slight slope-away eastwards. A test was made also for St. Athan, Glamorgan[5], a low-lying station (150 feet above mean sea level) in fairly level country, two miles from the coast, and the constant found to be 78.

Faust's formula was applied to Rothamsted data (using Dunstable data for 1500–1600 G.M.T.) and the constant found to be 78. The curve of H against G was used to forecast minimum temperatures for the "selected" radiation nights under consideration. The mean error was $-0{\cdot}6$°F., the mean absolute (positive) error $3{\cdot}1$°F. and the standard deviation of error $3{\cdot}8$°F. These values would appear to be about the order of magnitude of errors by this method. This method of forecasting ground minimum temperature uses only air data and presumably owes its accuracy to the correlation between air humidity with soil moisture and temperature conditions, etc.

In the following methods, using one or more soil variables, some attempt has been made to assess the relative importance of air temperature and moisture, and soil temperature and moisture conditions. Except where otherwise stated, θ and ϕ refer to 8 to 12 inches.

Method 1, *using soil temperature and soil moisture* (*state of ground and number of dry days*).—θ was plotted against G as base, and against each point was plotted the state of ground (at 0900 G.M.T.) and the number (X) of preceding dry days, that is, days on which the reported rainfall was nil or trace. It was found that, approximately, G did not fall below $\theta - 13{\cdot}5$ (see Fig. 2) but that for wet ground, particularly state of ground 1B, the points were rather close to this line (which may be referred to as the "wet limit"); for cases of baked soil (state of ground 0A) the points were normally about the line $G = \theta - 24{\cdot}5$

(the "dry limit") but the limiting value of G was as low as that given by the line $\theta - 28 \cdot 5$. Between the "wet limit" of $\theta - 13 \cdot 5$ and the "dry limit" of $\theta - 24 \cdot 5$, the value of G was roughly determined by X. This region was divided roughly into 15–17 days for March, 5 days for April and 3–4 days for May: the data suggests that from the soil-drying aspect, one dry day in May is equivalent to about one and a half dry days in April. This value is fairly consistent with

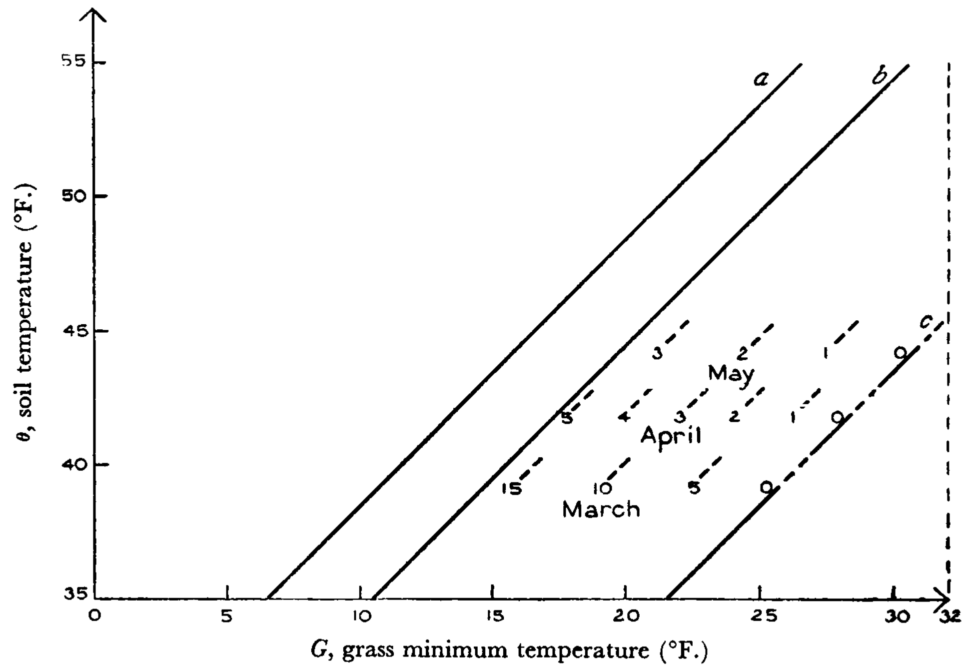


FIGURE 2—RELATION BETWEEN SOIL AND GRASS MINIMUM TEMPERATURES (°F.) WITH THE STATE OF GROUND AND PRECEDING DRY DAYS AT ROTHAMSTED

θ is the mean of observations taken at 0900 G.M.T. at depths of 8 and 12 inches.

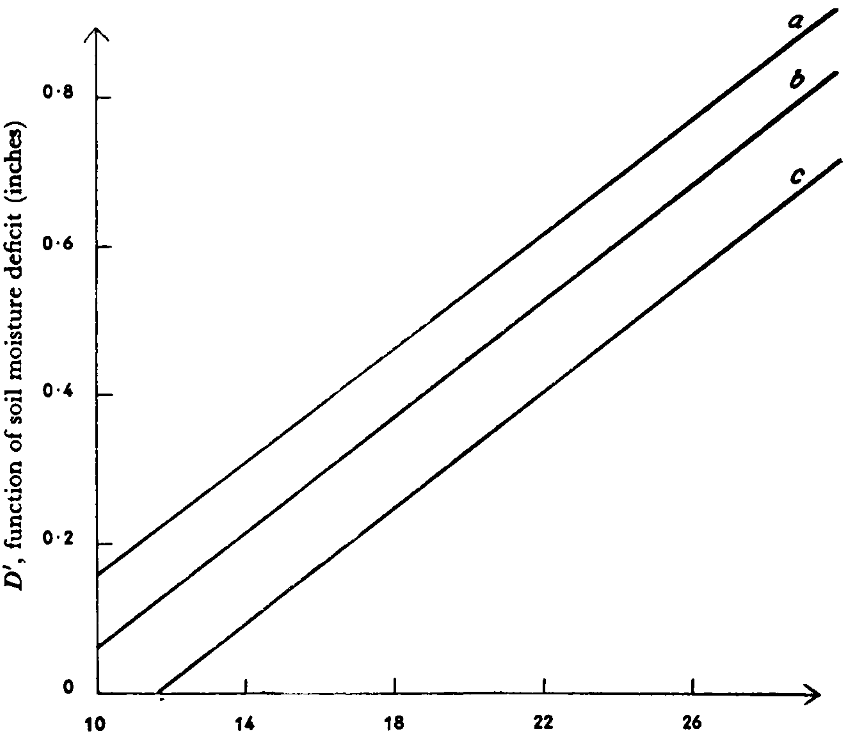
a: "baked" limit (oA), $G = \theta - 28 \cdot 5$
b: "dry" limit (oB), $G = \theta - 24 \cdot 5$
c: "wet" limit (1B), $G = \theta - 13 \cdot 5$
---: number of dry days

the approximate value of $1 \cdot 6$ for the ratio of May to April potential transpiration, as calculated from the Penman[6] formula. Excluding the three cases of soft wet ground, using the "wet" and "dry" limits for wet (state of ground oC, 1A) and baked (state of ground oA) soil respectively and assuming θ known, the mean error (calculated minus observed) was $-1 \cdot 6$°F. and the mean positive error $3 \cdot 8$°F. (for $G < 50$°F.). The mean errors were higher when the number of "dry" days (X') included days of $0 \cdot 01$ inches of rainfall.

Method 2, using soil temperature and soil moisture deficit (Penman).—This method incorporates soil moisture, not as in Method 1 by the number of dry days (X) but by a more complex measure (D), the soil moisture deficit in inches, based on the assumption that at the beginning of April the soil is at field capacity. The value of D was calculated, using the Penman[6] formula and correcting for actual sunshine and rainfall. D was plotted against a time base (April and May) and curves drawn for different values of ϕ, that is, $\theta_z - G$ (for 8 to 12 inches). It was found that for values of $D > 1 \cdot 50$, the value of G was under-estimated.

It is considered that this is due to the fact that D refers to a thick layer of the top soil and it is a much shallower layer of top soil which is relevant to the estimation of G. For example, a moist shallow layer of top soil presumably helps to maintain a high G, in spite of considerable drying out of lower layers. This may explain the lesser accuracy in late May as compared with mid-April. Errors were generally greater than by Method 1.

Method 3, *using soil temperature and soil moisture* (*deficit and number of dry days*).—This method uses both measures of soil moisture, D being plotted against X as base. A series of roughly parallel, equidistant straight lines were obtained for different values of ϕ. The results were again disappointing, presumably because of the use of D which refers to the moisture deficit of a layer of thickness far in excess of that of the layer which immediately affects frost liability.



ϕ, soil temperature minus grass minimum temperature (°F.)

FIGURE 3—RELATION BETWEEN SOIL TEMPERATURE, SOIL MOISTURE, AIR TEMPERATURE AND DEW-POINT

a: $H = 83+$
b: $H = 78$
c: $H = 73-$

$H = T + E/2$, where T and E are the dry-bulb temperature and dew-point (°F.) respectively at approximately 1500 G.M.T. on the previous day.

Method 4, *using soil temperature, soil moisture* (*recent "modified" deficit*), *air temperature and dew-point*.—This method introduces the moisture and temperature of both air and soil. Method 1 suggested that the most recent period of 5 days was most important in affecting G, and that to a much smaller degree the previous 5 days would (on the average) have some effect. It was considered that a useful parameter would be one which involves the weather of the last ten days, but with a gradually reducing weighting factor according to how long back the day is from the occasion for which G is required. Accordingly, a parameter D' (which may be referred to as "recent soil moisture deficit") was defined as

$$D' = (10d_1 + 9d_2 + 8d_3 + 7d_4 + \ldots + 2d_9 + d_{10})/10,$$

where d_n is the soil moisture loss during that day which is n days before the day for which G is required, as calculated in Method 2 above. D' should be better than D as an estimate of the soil moisture deficit in that it emphasizes the uppermost soil layer which has so great an influence on frost liability.

The value of D' was plotted against ϕ, and parallel lines were drawn for equal values of H (see Fig. 3), where H equals $(T + E/2)$, T and E being the dry-bulb temperature and dew-point respectively (in degrees Fahrenheit) at 1500 G.M.T. on the previous afternoon, based on Dunstable data. In this way, moisture and temperature for both air and soil are incorporated. The best fit for the line $H = 78$ appears to divide the observations equally, that is, $H = 78$ is the median. Similarly, the lines $H = 83$ and $H = 73$ were the upper and lower quartiles. Taking these lines to be 83 or more and 73 or less, respectively, and excluding cases of soft wet ground (state of ground 1B), the mean error, mean positive error and standard deviation (for $G < 50$°F.) were $+0 \cdot 09$, $2 \cdot 25$ and $2 \cdot 86$°F. respectively, on the assumption of θ being known, and $-0 \cdot 06$, $2 \cdot 78$ and $3 \cdot 47$°F. using forecast values of θ.

This method may be carried out also by plotting D' against H and drawing curves for different values of ϕ, or by plotting H against ϕ and drawing curves for different values of D'. The method of plotting D' against ϕ (as described above) was modified by replacing the lines of equal H by lines of equal dew-point (E), but errors were not reduced thereby.

In the method using D' with ϕ and lines of equal H, all cases (50 of 0B, 2 of 0C) of dry ground were within approximately 6°F., and seventy per cent were within 3°F. of the line with equation

$$\phi = \frac{60}{7}(3D' + 1)$$

$$\text{or } G = \theta - \frac{60}{7}(3D' + 1)$$

The cases of wet ground surface (9 cases of 1A) were within about 5°F. of the line with formula

$$G = \theta - \frac{60}{7}(3D' + 1) - 4.$$

The latter formula is suggested also for cases of baked soil (state of ground 0A), for three cases were within 2°F. and on the remaining occasion gradient wind could have seriously disturbed the stratification of air near the ground.

Method 5, using soil temperature, soil moisture (number of dry days), air temperature and dew-point.—This method, also, introduces the temperature and moisture conditions of both air and soil. The number of dry days (X and X') are plotted against H, and lines of equal ϕ are drawn. On the basis of ignoring dry days (X') in excess of 10 and using actual values of θ, the mean error, mean absolute error and standard deviation are respectively $+0 \cdot 26$, $2 \cdot 42$, $3 \cdot 03$°F. Although errors are a little larger than in Method 4, the method is simpler to apply, as X' requires less calculation than D'.

The lines of equal ϕ are parallel and equidistant and give rise to the formula

$$G = \theta - 30 + \frac{(H - 4\,X')}{5 \cdot 4}$$

The corresponding errors when X ($\leqslant 10$) is used instead of X' are $-1 \cdot 15$, $2 \cdot 70$, $3 \cdot 02$°F.

Method 6, *similar to Method* 5 *but using* (*a*) *no soil temperature data* (*b*) *soil temperature at* 4 *inches*—This method is similar to the previous method except that now the 4-inch soil temperature is considered, and also the forecasting of grass minimum temperature using soil moisture but without using any soil temperature data.

As before, X and X' (each $\leqslant 10$) are each plotted against H and then lines of equal G are drawn. Using X', the mean error, mean absolute error and standard deviation are $-0 \cdot 54$, $2 \cdot 60$ and $3 \cdot 06$°F. respectively for values of G less than 50°F. When X' is replaced by X the errors are $+0 \cdot 12$, $2 \cdot 65$, $3 \cdot 27$°F. respectively. As these are the total errors in the application of this method, it compares well with other methods and has the advantage of simplicity. The formula is

$$G = 5(H - X' - 19)/9.$$

When the 4-inch soil temperature at 0900 on the previous day exceeds 60°F., G is more accurately given by

$$G = (5H - 5X' - 68)/9.$$

Using 4-inch temperatures in this way, the corresponding errors were reduced to $-0 \cdot 31$, $2 \cdot 40$ and $2 \cdot 97$°F. Using actual and forecast values of the 4-inch soil temperature for 0900 on the day concerned gave no clear relation.

Method 7, *using soil moisture* (*recent "modified" deficit*), *air temperature and dew-point*.—This method also ignores soil temperature but uses D' instead of X'. It was found that the mean error, mean absolute error and standard deviation were respectively $-0 \cdot 19$, $2 \cdot 76$, $3 \cdot 41$°F. For cases in which either the forecast or actual value of the grass minimum temperature is $\leqslant 30$°F., the corresponding "errors" are $+0 \cdot 16$, $2 \cdot 59$, $3 \cdot 18$°F. The formula employed here was

$$G = 2H/3 - 11D' - 15 \cdot 7.$$

Conclusions.—Under radiation conditions:

(i) Using soil parameters, G can probably be more accurately forecast than when using only H (that is, $T + E/2$, where T and E are the dry-bulb and dew-point temperatures in degrees Fahrenheit at the hour of observation, 1500 G.M.T. on the previous afternoon).

(ii) Using H and X' (the number $\leqslant 10$ of consecutive preceding days on which the reported rainfall is nil, trace or $0 \cdot 01$ inch), a good estimate may be simply obtained (mean absolute error and standard deviation of $2 \cdot 60$ and $3 \cdot 06$°F. respectively). By making some allowance for soil temperature at 4 inches, the corresponding errors reduce to $2 \cdot 40$ and $2 \cdot 97$°F.

(iii) The accuracy of G forecasts could probably be increased by using

(*a*) a more suitable but probably more complex soil moisture parameter than those employed, (*b*) a better or more typical measure of the available terrestrial heat, which concentrates in the layer immediately below the ground surface, and

(*c*) a better measure of the daily incoming solar energy, which takes into account the angle of the sun's elevation during sunshine hours.

Both (*a*) and (*b*), however, may be difficult to obtain without more detailed measurements; observation of soil temperature and soil moisture at say 1800 G.M.T. would probably be useful.

(iv) The soil temperature at 4 inches and the mean temperature of the 8-inch and 12-inch levels, at 0900 G.M.T. can be forecast 24 hours ahead with an accuracy of the order of that shown in Table I. These forecasts which are based on wind and sunshine could probably be further improved by considering other factors such as humidity and soil moisture.

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SHORT-PERIOD VARIATIONS IN VISIBILITY

By A. C. BEST, O.B.E., D.Sc. and E.C. FIELDER

Summary.—Some autographic records of visibility at London Airport have been analysed to show the frequency of short-period variations of visibility on occasions when the visibility is generally below 1,100 yards and is patchy. In such conditions the chance of a change of 30 per cent in visibility is about nine per cent after four minutes and 26 per cent after 20 minutes if the initial visibility is between 400 and 1,100 yards. If the initial visibility is between 300 and 400 yards the corresponding figures are 10 and 39 per cent respectively.

Introduction.—It is a matter of common experience that fog is frequently patchy and that appreciable variations in visibility can occur in a few minutes. It is not easy, however, to obtain evidence of the frequency and magnitude of these variations. It would be difficult for a human observer to make a long series of completely independent eye observations at intervals of a few minutes while use of the Gold visibility meter would lead to results affected by changes in the dark adaption of the eye.

For several years there has been in use at London Airport a photoelectric visibility meter which records the visibility over a path length of approximately 300 yards. There are difficulties about accepting the indications of such an instrument as a measure of visibility for the purpose of synoptic reports but these difficulties are not so weighty if the instrument is used to indicate changes in visibility. The London Airport instrument is particularly well adapted to indicate marked short-period variations since the record consists of a series of dots, at four-minute intervals, on a chart. It is thus a simple matter to determine from the record the change in visibility after four, eight, twelve, etc. minutes.

The data used.—By straightforward inspection of the charts of the visibility meter six days were selected on which the visibility was generally below 1,100 yards and was also subject to marked variations. The visibility records for the periods of variable visibility for these six days have been analysed, as described below, and the results of the analyses combined for the six days. The results may be regarded as giving a statistical picture of what may happen when the visibility is variable.

The occasions selected occurred on the 8th, 11th, 15th and 17th of October and 1st and 6th of December, in 1956. On each day the period selected occurred in the evening or very early morning. Naturally on most of the selected days the pressure distribution resulted in London Airport being influenced by an area of high pressure with a wind which was calm or, at most, a few knots.

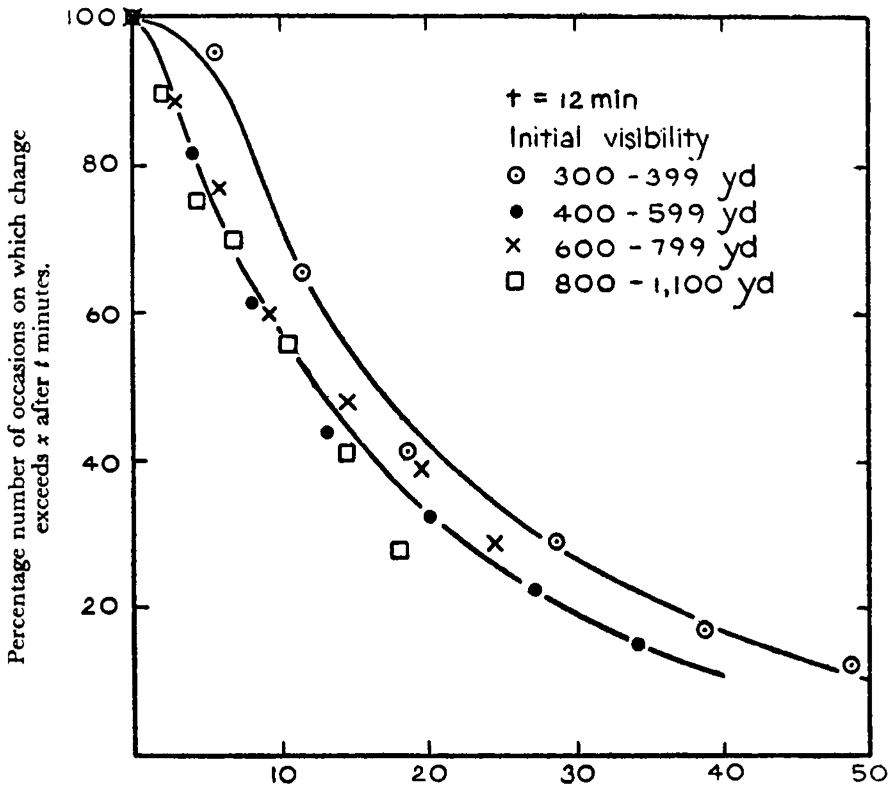

FIGURE 1

Method of analysis.—The visibility corresponding to each dot was tabulated (to the nearest five yards). Next the changes in visibility in the intervals 4, 8, 12, 16 and 20 minutes after each dot were tabulated. The number of changes of 0 to 15, 20 to 35, 40 to 60, 65 to 95, 100 to 130, 135 to 170 and greater than 170 yards were determined for each day and for each interval, positive and negative changes being kept separate. In this part of the analysis different frequency tables were compiled according to the visibility at zero time, the ranges of initial visibility separated being 300 to 400, 400 to 600, 600 to 800 and 800 to 1,100 yards (there were too few observations with initial visibility below 300 yards to justify a separate class). After adding together the frequencies for the six days, inspection of the tables showed no significant difference between the frequency of positive and negative variations in visibility. This distinction was accordingly abandoned. The next step was to convert the frequency figures to cumulative percentage frequency figures showing the percentage number of occasions on which the change in visibility over the appropriate interval of time exceeded a specified value. As might be expected the results showed a marked dependence on the initial visibility. Accordingly the variations in visibility were expressed as percentages of the visibility at the middle of the range of visibility in which the initial visibility fell. It is in this form that we give the results below.

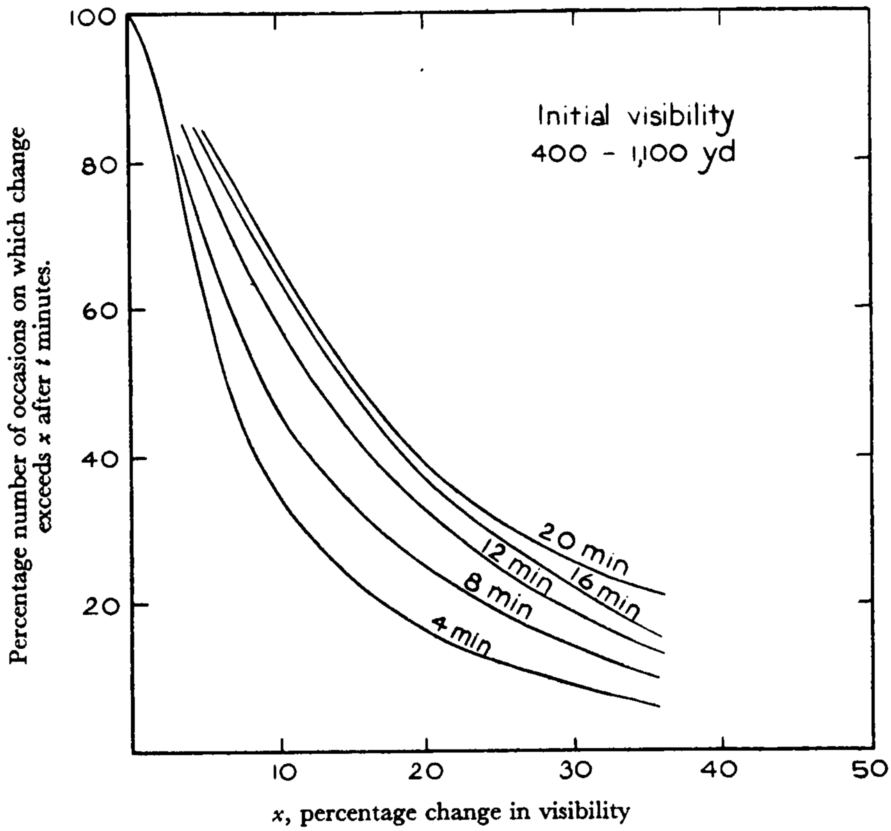

FIGURE 2

Results.—The percentage change in visibility was plotted against the percentage number of occasions on which the change was exceeded for each time interval and for each range of initial visibility. The plotted points for the 12-minute interval are shown in Figure 1. This plot is typical of those for the other four intervals and illustrates the following features which were common to all five plots:

(*a*) The points from all initial visibility ranges between 400 and 1,100 yards show little scatter from one mean curve. (The 4-, 8- and 20-minute plots showed less scatter than Figure 1).

(*b*) There is a tendency for the frequency of large variations to be less than indicated by the mean curve if the initial visibility is in the 800 to 1,100-yard range (this was not noticeable for 4 and 20 minutes).

(*c*) The variations are more frequent if the initial visibility is in the 300 to 400-yard range than with other initial visibilities.

The mean curves for all time intervals are shown in Figure 2 (initial visibility 400 to 1,100 yards) and Figure 3 (300 to 400 yards). The increase in frequency of variations with increasing time is, as one might expect, rapid at short times and slower for the larger times.

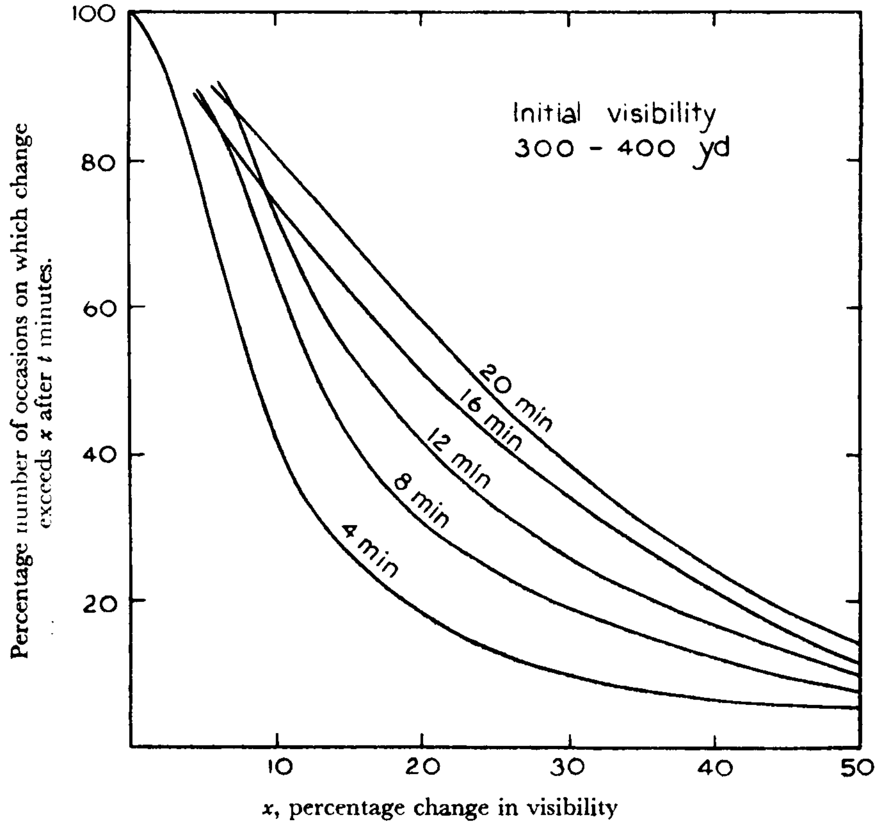

FIGURE 3

From the aviation point of view the most interesting aspect of these results is the frequency of large changes after very short intervals. The curves in Figures 2 and 3 show that after an interval of only four minutes the change in visibility in a patchy fog is likely to exceed 30 per cent on about 10 per cent of occasions. After 20 minutes the same variation is likely to be exceeded on 26 per cent of occasions if the initial visibility is between 400 and 1,100 yards and 39 per cent of occasions if the initial visibility is between 300 and 400 yards.

THE CLEARANCE OF FROST FOLLOWING THE ARRIVAL OF A CLOUD SHEET DURING THE NIGHT

By W. E. SAUNDERS, B.Sc.

The effectiveness of a cloud sheet in dispersing radiation fog on a large proportion of occasions has been discussed in a recent paper.[1] The physical processes were considered, and it was concluded that the most important features were the cloud height and the heat flux from ground to air, the latter being determined by the soil-to-air temperature gradient as well as by the characteristics and state of the soil.

The present note deals with a rather similar problem, the effect on temperatures near the ground of the arrival of a cloud sheet on a radiation night, in the absence of fog, when before the cloud arrives the grass or air temperatures are below freezing. It attempts to establish under what conditions the temperatures at these levels will rise above freezing following the arrival of cloud.

The work is based on the ordinary hourly synoptic reports from Exeter Airport, together with hourly readings of the grass temperature (using the grass thermometer as an ordinary thermometer), and of a two-inch bent-stem earth thermometer. The grass readings were supplemented on many occasions by readings of the minimum index of the thermometer, so that the minimum between hourly observations was also included. Readings of an eight-inch bent-stem earth thermometer were made twice daily.

The most common temperature structure near the ground during a radiation night is that the eight-inch temperature is a few degrees higher than the two-inch temperature, while the latter is appreciably higher than the grass temperature. The heat flux in the soil is therefore directed strongly towards the surface. When this applies, it has been observed that the grass temperature responds very rapidly to changes in the state of sky. This point is illustrated in Figure 1, which gives the two-inch earth and grass temperatures for the night of 17–18 May 1954, which was a night with calm surface wind but with frequent changes in the cloud cover.

All occasions during the period November 1953—November 1958 in which the grass temperature was below 32°F prior to the arrival of a continuous cloud sheet were examined. Only cases where an eight-eighths cloud layer arrived were included, because if the cloud amount reported is less it is impossible to decide from the records whether or not the cloud was overhead. Cases in which the cloud arrived towards the end of the night, or in which it appeared freshening winds might have caused a rise in temperature, were excluded. The remainder were plotted in Figure 2, in which the parameters used are:—(*a*) the cloud height, which was usually a cloud-searchlight measurement, and (*b*) the sum of the grass temperature and the two-inch earth temperature immediately before the arrival of cloud. This temperature parameter was chosen to take account of the two facts (i) that the higher the grass temperature is initially, the more readily it will rise above 32°F., other things being equal (for example, if the grass temperature is 30°F. it will rise above 32°F. more readily than if it started from 20°F.) and (ii) the higher the two-inch earth temperature the greater the soil-to-grass temperature gradient, and hence the stronger the heat flux towards the surface.

In Figure 2 the cases have been separated according as the grass temperature rose above 32°F. following the arrival of cloud (plotted as small circles), or remained 32°F. or below (marked ×). In general, in the frost clearance cases, it was found that the temperature rose above 32°F. within a period which varied from a few minutes to two hours, and in the ×-cases temperature remained below freezing however long the period of cloud cover. It was found that the diagram could be divided into three zones by lines AB and CD, such that in all cases to the left of AB the grass temperature rose above freezing, with the exception of three occasions when there was snow cover, marked *, and that in all cases to the right of CD the grass temperature remained below 32°F. The area between AB and CD represents a near-equilibrium transitional stage in

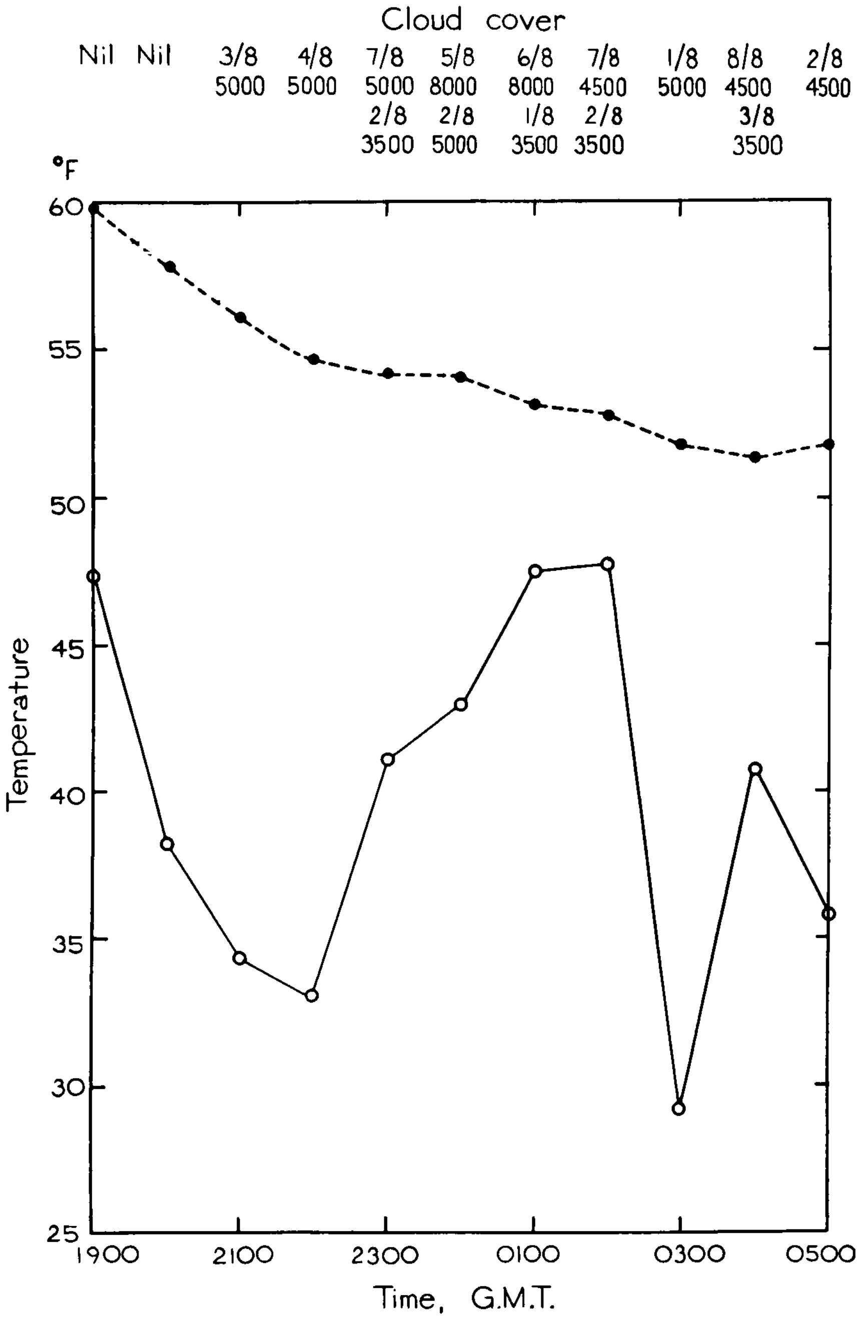

FIGURE 1—EARTH AND GRASS TEMPERATURES AND CLOUD COVER AT EXETER, 17–18 MAY 1954

The continuous line is the grass temperature and the broken line is the two-inch earth temperature.

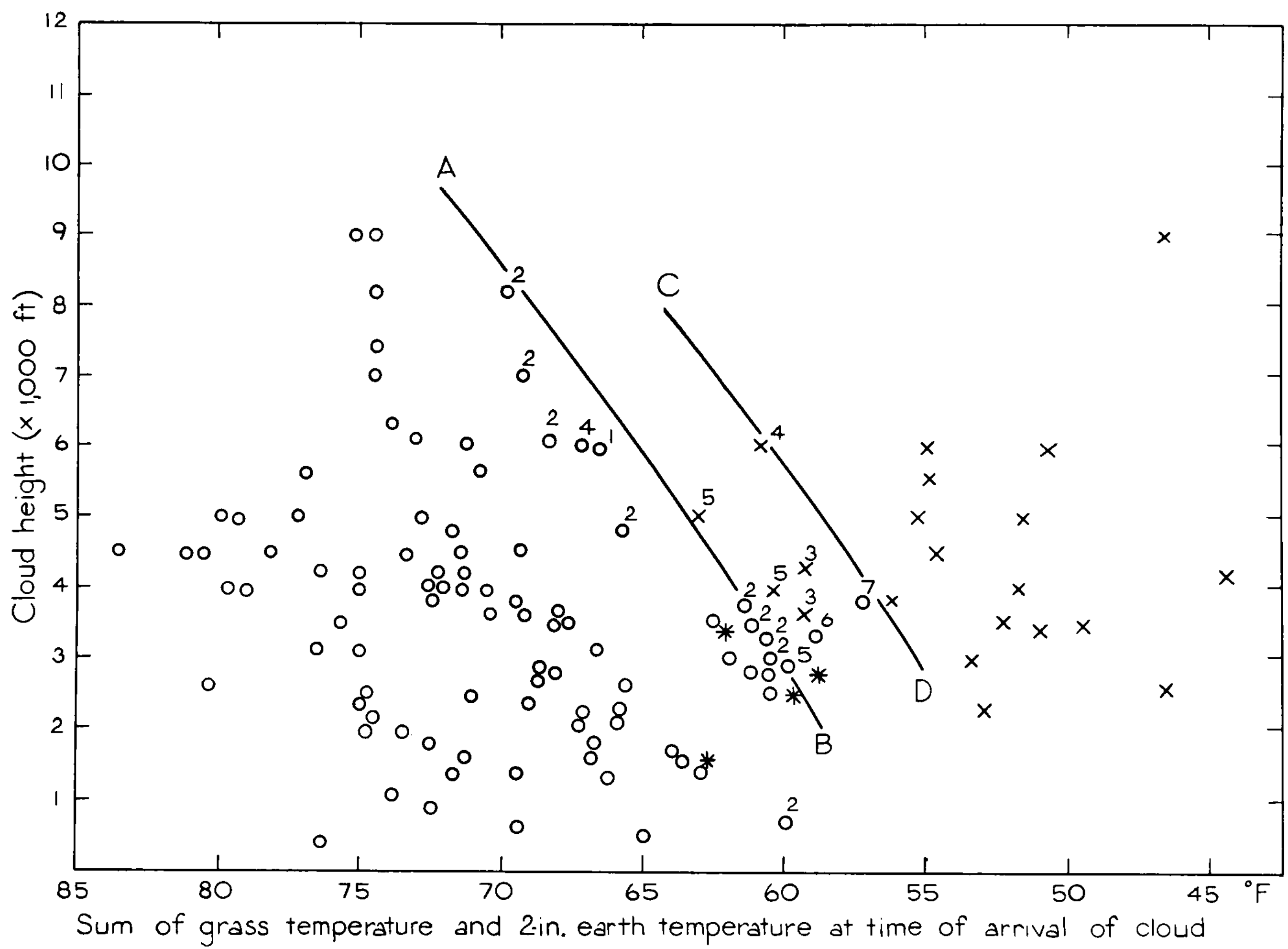

FIGURE 2—THE EFFECT OF THE ARRIVAL OF A CLOUD SHEET ON FROST AT GRASS LEVEL

o: grass temperature rose above 32°F. × : grass temperature remained 32 F or below. ✱: cases with snow cover.

The small figures adjacent to some symbols give the time taken for the temperature to rise above freezing in o-cases, and the period of cloud cover in -cases.

which an appreciable period of cloud cover is necessary to clear the frost. The times have been plotted in hours by small figures adjacent to the symbols in this portion of the diagram, and the comparatively small number of cases of this type available suggest that the period required for frost clearance for cases between AB and CD is at least six to seven hours. In addition to the cases included on the diagram there were eight occasions of cirrostratus in which the grass temperature remained 32°F. or below.

The range of grass temperatures in the cases considered was from 11·5 to 31·9°F. The lowest initial grass temperature in a case when frost cleared was 20°F. The two-inch earth temperatures were between 32°F. and 52°F., except for three occasions in the first week of February, 1954, when they were about 31°F. The lowest initial two-inch temperature in a frost clearance case was 33·4°F.

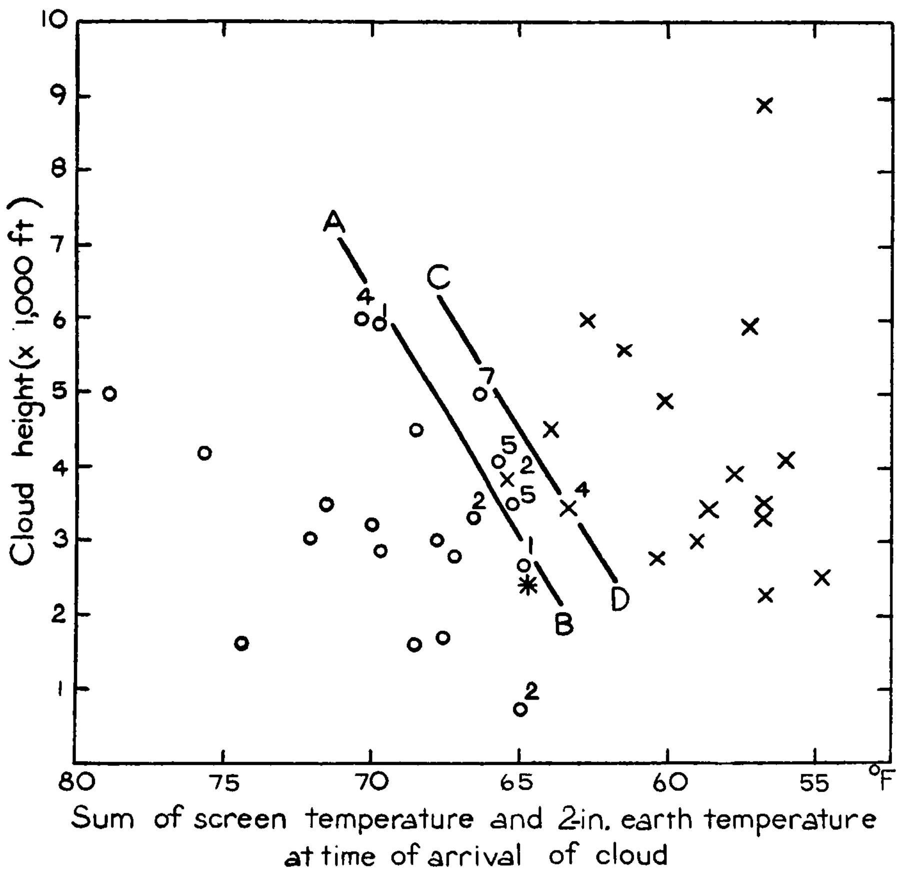

FIGURE 3—THE EFFECT OF THE ARRIVAL OF A CLOUD SHEET ON FROST AT SCREEN LEVEL

o: screen temperature rose above 32°F.
×: screen temperature failed to rise above 32°F.
*: cases with snow cover.
The small figures adjacent to some symbols give the time in hours taken for temperature to exceed 32°F in the o-cases, and period of cloud cover in the ×-cases.

A similar exmination was made of the effect of cloud cover on the screen-level temperature, when this was 32°F. or below when the cloud sheet arrived. Figure 3 was constructed along similar lines to Figure 2, except that the temperature parameter is now the sum of the screen and two-inch earth temperatures before the arrival of cloud. The number of cases is smaller than on Figure 2, but a similar distribution occurs. The lines AB and CD are shifted in the direction of higher temperature, as might be expected. Cases in the transitional zone between AB and CD appear to require a period of five to seven hours' cloud cover to raise the screen temperature above 32°F. There were, in addition, six cirrostratus cases in which the frost persisted.

As might be expected, the annual variation of the incidence of non-clearance of frost cases was that most occurred in January and February, but there were cases as early as 1 November and as late as 20 March.

It is apparent that Figures 2 and 3 can be used for forecasting the dispersal of frost at Exeter, except when there is also snow cover, provided that observations are made of the grass and two-inch earth temperatures in addition to the normal synoptic routine. When there is snow cover the temperature would presumably remain at or below freezing even after the arrival of cloud, unless the cover of snow was very thin and sparse.

REFERENCE

1. SAUNDERS, W. E.; The clearance of water fog following the arrival of a cloud sheet during the night. *Met. Mag., London*, **89**, 1960, p. 8.

VARIATION IN SHOWER ACTIVITY AT ACKLINGTON

By J. BRIGGS, B.A. and J. JOHNS

Introduction.—During the long spell of cold northerly winds in February and March of 1958 an apparent diurnal rhythm of shower activity was noticed. It seemed that showers were most likely between 0700 and 1000 G.M.T. and between 1600 and 1800 G.M.T. Since showers at that time of the year are frequently of snow and may cause rapid and pronounced deterioration of the weather it seemed worthwhile to undertake a wider investigation. This was done initially for the years 1953–57 and later extended to cover the years 1948–57.

Clearly shower activity at Acklington is largely influenced by the proximity of the North Sea and by the sheltering effects of the Cheviots to the west. The situation of Acklington is shown on Figure 1.

Method.—Throughout the period 1948–57 the hourly distribution of reports of showers was summarized on a monthly basis. A report of a shower was allocated to the appropriate hourly period in which the shower commenced. If a further shower occurred during this same hour it was disregarded and if the shower continued into the next hour no further record was made unless it was clear from the remarks column of the register that the shower had ceased and a new one had commenced. The reports of showers were also subdivided according to the general prevailing wind at about the time of occurrence of the shower, not necessarily the wind direction during the shower. If no pronounced direction was apparent then the wind direction was logged as variable.

Results.—Table I shows the number of reports, for each hour of day, throughout the period 1948–57, sub-divided according to wind direction. The maximum frequency is with south-westerly winds though there is a secondary maximum for winds between north-west and north. During the night, however, the maximum frequency occurs with northerly to north-westerly winds. These differences are, of course, mainly due to the fact that cold northerly airstreams across the North Sea have a tendency to produce showers by day and night, whereas the south-westerly winds, having a long land-track, tend to have a normal nocturnal decrease of showers.

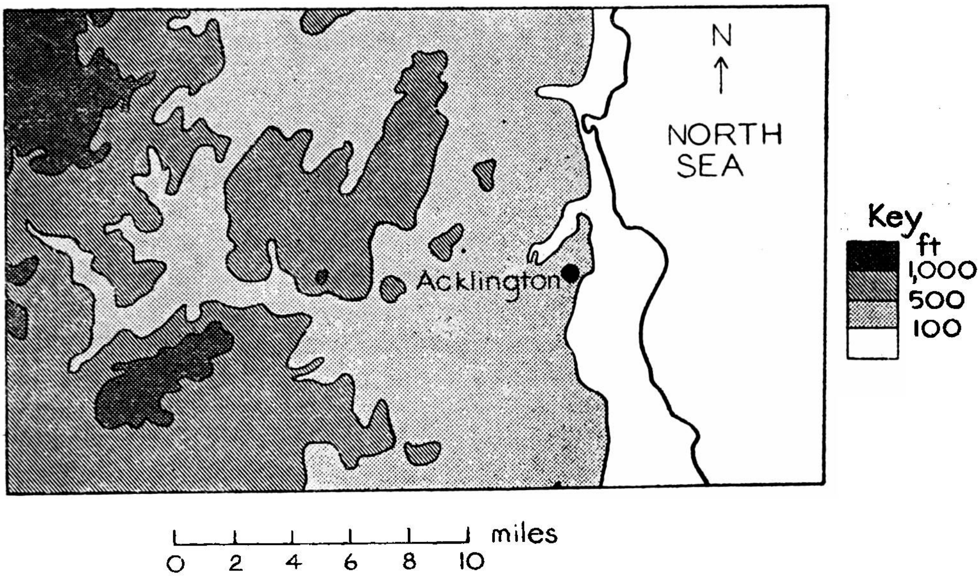

FIGURE 1—LOCAL TOPOGRAPHY AROUND ACKLINGTON

The marked absence of showers with southerly winds is probably due to the relative infrequency of such winds because of sea-breezes, katabatic winds etc. No attempt has been made to allow, in the analysis, for frequency of winds. With westerly winds the notable feature is the concentration of showers in the afternoon and especially the sharp rise in frequency between 1100–1200 and 1200–1300 G.M.T. The sheltering effect of the hills may be responsible for this and also probably accounts for the reduction of showers as compared to south-westerly winds.

Table II shows the number of reports for each hour, irrespective of wind direction, summarized monthly. Over the year the mean diurnal variation is seen to follow fairly closely the diurnal variation of temperature, with maximum frequency of showers in the afternoon but with secondary maxima suggested at 0900–1000 and 1600–1700 G.M.T. The monthly variation shows a surprisingly steady tendency for showers through summer and autumn but then a sharp rise in the winter months to a maximum in February followed by a sharp drop in the spring months. The increased frequency of showers in winter is due to the continued shower activity through the night and it is shown, by separate monthly summaries sub-divided according to wind direction, to be associated with northerly winds.

It seems reasonable to consider that the seasonal variation is connected with the variation in the difference between the land and sea temperatures. For this reason the months of February and August, that is, the months of lowest and highest land temperatures, are considered separately.

TABLE I—HOURLY DISTRIBUTION OF SHOWERS AT ACKLINGTON FOR VARIOUS WIND DIRECTIONS, 1948–57

Time G.M.T. *hours*	N	NE	E	SE	S	SW	W	NW	Variable	Total
					Wind direction *number of reports*					
00–01	18	13	7	1	0	10	6	19	2	76
01–02	12	10	3	2	0	10	11	18	1	67
02–03	10	9	4	2	1	6	3	24	0	59
03–04	15	6	3	2	5	7	6	17	0	61
04–05	9	6	3	2	3	9	5	18	1	56
05–06	13	5	7	0	0	10	9	16	2	62
06–07	20	9	5	2	1	11	10	26	3	87
07–08	25	11	9	5	2	15	11	29	4	111
08–09	26	15	10	1	0	21	11	32	5	121
09–10	32	15	16	4	0	42	14	43	3	169
10–11	28	17	17	5	6	38	23	36	3	173
11–12	40	24	17	11	4	55	21	42	6	220
12–13	36	25	18	9	6	61	51	31	8	245
13–14	40	22	20	22	11	42	46	22	13	238
14–15	34	21	19	13	3	40	48	23	14	215
15–16	23	22	16	16	7	44	38	19	11	196
16–17	33	21	16	16	8	38	34	27	13	206
17–18	28	8	13	11	5	27	19	21	11	143
18–19	20	4	11	7	6	30	15	22	10	125
19–20	23	7	10	6	3	28	14	19	14	124
20–21	19	14	4	9	3	20	15	30	9	123
21–22	19	17	5	6	5	18	6	13	5	94
22–23	21	8	9	7	3	13	9	16	4	90
23–00	11	12	7	5	2	18	9	14	3	81
all hours	555	321	249	164	84	613	434	577	145	3,142

TABLE II—HOURLY DISTRIBUTION OF SHOWERS AT ACKLINGTON FOR EACH MONTH 1948–57

Time G.M.T. *hours*	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
							Month *number of reports*						
00–01	11	19	6	5	6	3	4	0	2	5	9	6	76
01–02	10	15	6	4	5	3	2	2	2	3	6	9	67
02–03	4	15	5	6	4	2	0	1	5	4	7	6	59
03–04	6	10	8	7	4	0	2	3	1	6	7	7	61
04–05	10	10	2	4	3	4	4	1	3	4	4	7	56
05–06	10	13	6	3	3	1	2	1	3	5	5	10	62
06–07	11	17	7	6	7	3	2	4	4	5	8	13	87
07–08	12	26	11	8	9	3	1	5	7	10	5	14	111
08–09	18	26	10	7	7	4	6	4	8	10	8	13	121
09–10	15	40	12	11	13	8	9	7	8	14	14	18	169
10–11	14	27	13	13	16	17	13	8	10	18	13	11	173
11–12	21	27	16	18	20	24	21	15	17	12	12	17	220
12–13	24	34	17	16	20	20	16	23	23	19	17	16	245
13–14	22	29	14	27	22	23	23	23	21	13	7	14	238
14–15	22	24	12	19	21	15	16	22	18	17	16	13	215
15–16	15	19	16	19	17	19	18	21	11	16	12	13	196
16–17	14	29	18	20	15	15	18	18	18	13	12	16	206
17–18	15	22	8	11	16	11	15	10	12	8	7	8	143
18–19	15	24	4	11	11	10	8	13	6	9	8	6	125
19–20	13	9	7	7	14	13	7	16	11	7	9	11	124
20–21	15	20	7	9	12	8	8	6	9	7	9	13	123
21–22	15	13	6	7	7	2	4	8	8	6	5	13	94
22–23	15	17	6	6	8	6	3	1	6	5	10	7	90
23–00	7	17	5	6	4	4	9	5	4	5	8	7	81
all hours	334	502	222	250	264	218	211	217	217	221	218	268	3,142

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CUMULONIMBUS TOP ABOVE TROPOPAUSE OVER NORTH-EAST BELGIUM

(see p. 56)

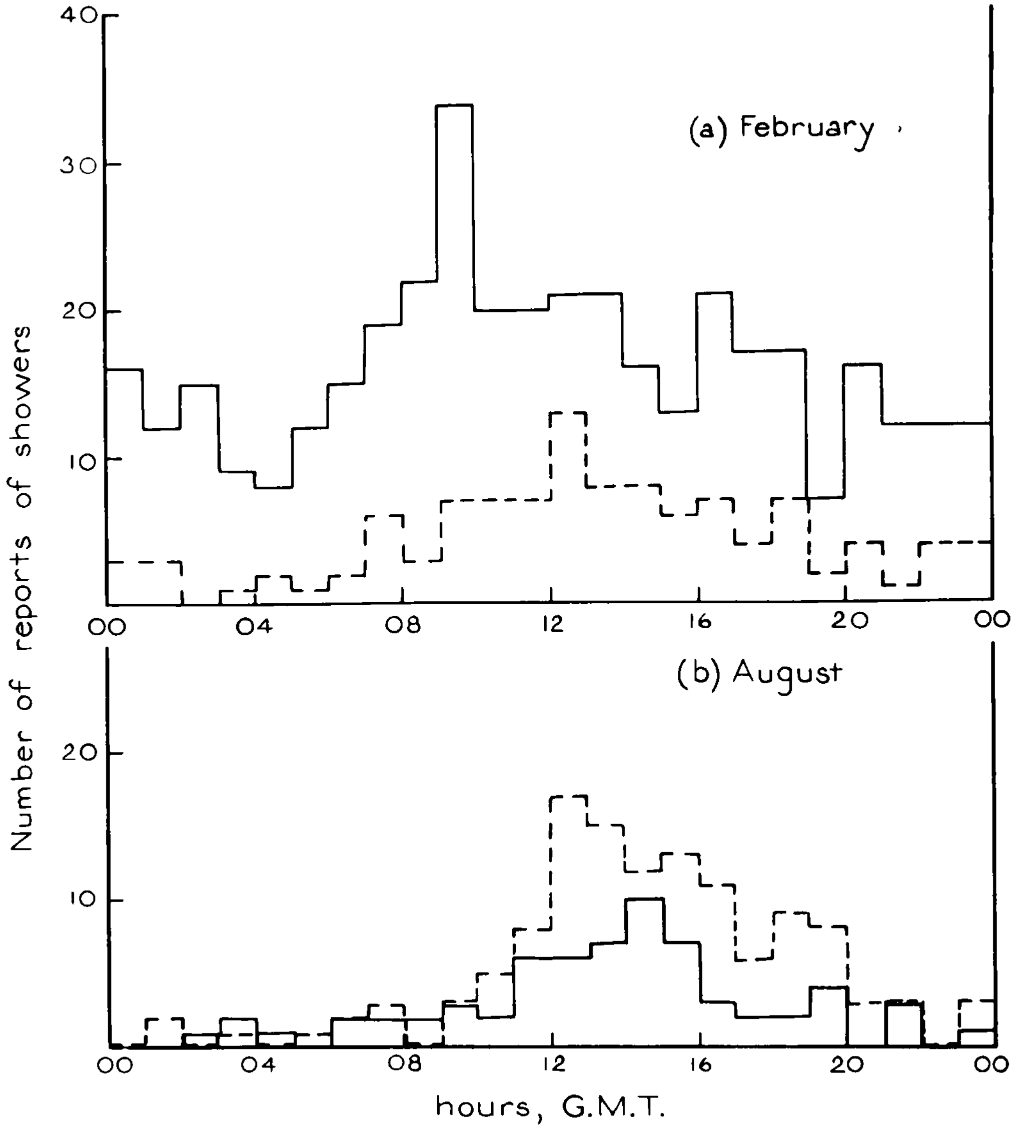

FIGURE 2—HISTOGRAMS OF SHOWER FREQUENCY FOR FEBRUARY AND AUGUST 1948–57

Continuous lines: winds from north-west, north, north-east and east.
Broken lines: winds from south-east, south, south-west and west.

Figures 2(*a*) and 2(*b*) are histograms of the shower frequency, for February and August respectively, sub-divided into two groups of wind; the groups taken are north-west, north, north-east, east and south-east, south, south-west, west, that is, basically "sea" and "land" winds (allowing for the normal veer between the surface and 2,000 feet).

The Figures illustrate the much greater shower frequency in February. This is seen to be due to winds from the sea; Figure 2(*a*) shows the relatively small diurnal variation of such winds but the interesting feature is the tendency for a morning maximum, between 0900 and 1000 G.M.T., with a definite decrease in the afternoon followed by a resurgence of shower activity around 1600–1700 G.M.T.

An explanation for the morning maximum may be sought in terms of the effects of the katabatic winds and nocturnal cooling; the combined effect is to produce a very cold wind over land which is backed from the relatively cool wind over the sea. A zone of frontal convergence is set up in the vicinity of the coastline and this front accentuates the showers. The front reaches its maximum intensity around sunrise and is dissipated during the morning; so the shower frequency at first rises but then falls as the front disappears. Northerly, north-westerly and easterly winds all show the morning maximum when separately considered but north-easterly winds do not. It may be that, since the north-easterly winds are connected with the most direct approach of showers from the sea, the influence of the katabatic wind is then unable to extend as far as Acklington.

The resurgence of shower activity toward dusk can possibly be explained by radiational cooling of the top part of cumuliform cloud advected from the sea whereas the lower-level temperatures are maintained over the sea. When separately considered, north-westerly, northerly and easterly winds show the evening maximum around 1700–1800 G.M.T. whereas north-easterly winds show a minimum at this time followed by a maximum at 2000–2200 G.M.T.

Figure 2(*b*) indicates that in August the greatest shower activity occurs with winds off the land. The diurnal variation is now more normal and the shower frequency is greatest in the afternoon though again there is a suggestion of a resurgence of showers toward dusk in the secondary peaks at 1800–2000 G.M.T.

Summary.—Although the main features of the shower activity at Acklington can readily be explained in terms of the influence of the surrounding hills and sea there are one or two points of interest. In particular the suggestion of a morning maximum, for showers with northerly winds in the winter months, is confirmed. This can be a useful forecasting guide, especially in February. Similarly the indication of renewed shower activity towards dusk seems of value.

METEOROLOGICAL OFFICE DISCUSSION

Icing

At the Monday Discussion on 19 October 1959, Mr. R. F. Jones opened with a general survey of the problem of forecasting aircraft icing and was followed by Mr. A. F. Crossley who discussed icing statistics obtained from transport aircraft over the North Atlantic. Mr. P. Graystone completed the formal presentation of the subject with a consideration of the effects of aerodynamic heating on ice accretion. A discussion followed.

In his opening statement Mr. Jones pointed out that meteorologists do not in fact forecast aircraft icing but the occurrence of supercooled water on the route to be flown. How a particular aircraft will react to flight in clouds containing supercooled water is a complex problem to which a precise answer has still not been found. The efficiency with which various parts of an aircraft surface collect water drops[1] depends on the shape of the surface, its speed and the drop sizes. An edge having a small radius of curvature disturbs the airflow very little and most drops are caught, but a bluff object so distorts the airflow that many of the smaller drops are carried round the object and lost. The leading edges of wing and tailplane or radio masts, for example, collect more water, and therefore ice more rapidly, than other parts of the aircraft. Once ice begins to form the shape of the collecting surface is changed and hence the efficiency with which it collects water also changes. The efficiency of catch increases with the speed of the aircraft but the speed also has other effects. If icing occurs the rate of icing increases with the speed since, apart from the greater efficiency of catch, a greater volume of air is swept out per second by unit area of forward-facing surface. On the other hand a fast aircraft heats up more by kinetic heating than does a slow one and there may be occasions when a fast aircraft will remain wet while a slow one collects ice. The calculation of the magnitude of kinetic heating, however, is extremely difficult, especially in potential icing conditions, and some reports of icing experienced by jet aircraft suggest that the protection provided by kinetic heating may sometimes be small. Early experience with the Proteus engine of the Britannia aircraft, before successful modifications were introduced, has shown that heated surfaces can collect ice even in dry ice-crystal cloud. The melting of ice crystals hitting the heated surface extracts the latent heat required from the surface until its temperature is reduced to 0°C. Subsequent ice crystals then stick on the wet surface so formed. This raises the question whether some ice formation might not occur on the leading edge of a very fast aircraft when flying in ice-crystal cloud without any supercooled water being present.

In forecasting the presence of supercooled water on a particular route we have first to forecast the clouds on the route, itself often very difficult, and then forecast the supercooled water content of these clouds, which is even more difficult. The supercooled water content of a portion of a cloud, which in theory can be calculated[2] from a knowledge of the temperature at the level for which the content is required and the initial water content of the air which ascended to form the cloud, can be modified in a number of ways: by the freezing of some or all of the water droplets either because the temperature is low enough or because they have come in contact with ice crystals, by the fall-out of drops which have grown large enough to obtain a significant fall-speed, by the fall-in of other large drops from above and by mixing with other air of different water content or with cloud-free air at the edges of the cloud. In addition the *rate* at which free water is made available which is, of course, dependent on the speed of ascent of the air has been shown[3] to be an important parameter. It is optimistic therefore to expect that we shall ever be able to forecast supercooled water content with precision but Mr. Jones considered that the most important criterion to decide on in forecasting is whether the air is ascending at a rate sufficient to maintain saturation with respect to water in the presence of any ice crystals there may be. Best[3] has shown this condition to be increasingly difficult to meet as the number of ice crystals increases, and, since the rate of production of ice crystals in ascending air is a function of temperature (see, for example, *The physics of clouds*[4]), one would expect the condition to be fulfilled readily at temperatures down to −15°C. in freshly-formed cloud but to become more difficult at lower temperatures or as the cloud ages and crystals settle down from above. An examination of aircraft reports[5] helps to confirm the importance of this criterion and lays particular emphasis on the occasions when severe icing was encountered in active frontal cloud and in situations where orographic uplift led to up-currents greater than normal within the cloud.

Mr. Crossley discussed reports of ice accretion which are included in routine observations made by crews of transport aircraft on North Atlantic routes. These reports are transmitted in POMAR or AIREP code and use was made of all those received at London Airport in January and July in the years 1955–57. The reports contain a varying amount of meteorological information, but they nearly all contain the ambient temperature, corrected for instrumental error and airspeed, while the reporting of ice accretion, when it occurs, is mandatory. The tabulated reports were punched on to Hollerith cards for ease of sorting.

Although icing regions tend to be avoided and de-icing equipment is used when necessary, nevertheless icing is reported in January on nearly four per cent of all occasions; out of more than 6,000 occasions with temperature of 0°C. or less, there were 201 reports of light icing, 35 of moderate and four of severe icing; the classification however is subjective. A slide showed the distribution of icing reports with temperature. The shape of the histogram is partly conditioned by the frequency distribution of the temperatures themselves, which in turn reflect the aircraft heights; these ranged from 6,000 to 25,000 feet with a strong maximum at 18,000–19,000 feet. Attention was drawn to the rarity of icing at temperatures above −4°C.; this is attributable to the effects of kinetic heating, the aircraft speeds being in the region of 200 knots. Further, several cases of icing were reported at −40°C. to −44°C., temperatures at which all the cloud particles are usually thought to be frozen.

The frequency of icing as a percentage of all occasions, grouped in steps of 2°C., is roughly constant at about five per cent from −4°C. to −25°C. apart from a peak at −6°C. to −7°C.; the frequency decreases down to −39°C., but then there is another, smaller, peak at −42°C. to −43°C. Another slide showed the percentage frequency of icing in cloud in steps of 4°C. The features of this distribution are a pronounced maximum of 45 per cent at −4°C. to −7°C., followed by an irregular decline, and then another maximum of 19 per cent at −40°C. to −43°C. In this latter range there were eight reports of icing out of 203 temperature observations, of which 42 were in cloud.

In July, although the temperature observations below 0°C. exceed the January figure by about one-third, the number of reports of icing is much smaller, 142 against 240. Moreover, with the higher temperatures of July there are very few observations below −35°C., and −29°C. is the lowest at which icing was reported. There were 16 reports of moderate icing and no reports of severe icing in July. The frequency of icing in cloud was again small down to −3°C., but a value close to 20 per cent was maintained from −4°C. to −11°C.

The reduced frequency of icing in cloud in summer (average 14 per cent) against winter (average 21 per cent.) is perhaps to be explained by the greater frequency of convective clouds over the sea in winter, since these are the clouds most favourable for icing, but there may well be other reasons to account for the seasonal difference in the risk of icing.

Mr. Graystone discussed from a theoretical point of view the effect of aerodynamic heating on airframe icing. For flight in cloud, the estimation of the equilibrium surface temperature of a high-speed aircraft is a matter of some complexity. In supercooled water cloud, there are five terms to be considered. Two of these represent heat gained, namely, aerodynamic heating and kinetic heating due to the impact of water droplets. Heat is lost in three ways: by convection, by evaporation, and by heating the supercooled droplets to the equilibrium temperature. Balancing these terms yields an equation of the form

$$\beta\frac{V^2}{2JC_p} + \alpha\frac{V^2}{2J} = \beta\,(t_0-t) + \frac{K}{C_p}L\beta\frac{e_0-e}{p} + \alpha(t_0-t).$$

This equation relates the equilibrium temperature t_0 to the ambient temperature t, the pressure p, and the aircraft's velocity V. It involves the rate of catch of water droplets α, and a heat transfer coefficient β. Both of these are highly variable, and it is necessary to make some assumption about them before an equilibrium temperature can be derived. Messinger[6] suggests using the ratio α/β,

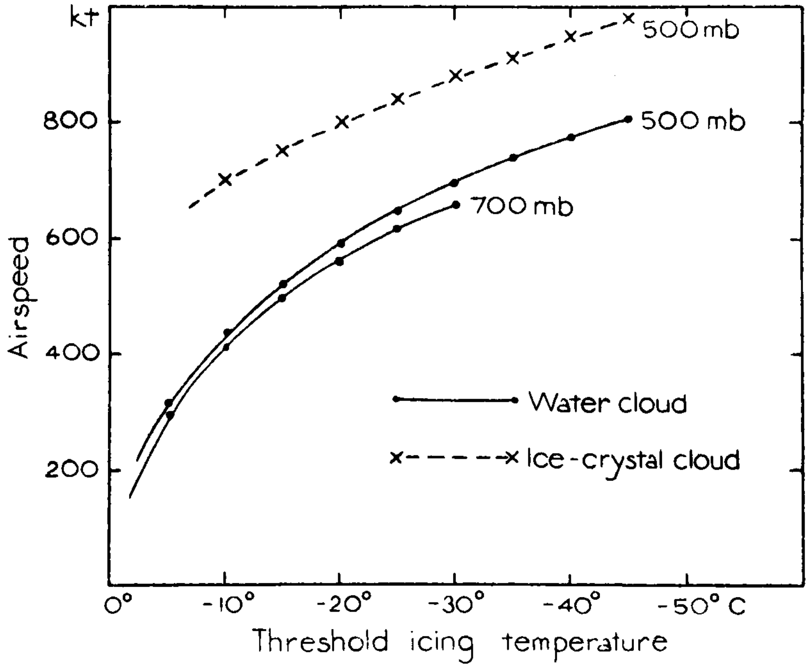

FIGURE 1—ESTIMATED MAXIMUM TEMPERATURES FOR AIRFRAME ICING AT GIVEN AIRSPEEDS

and quotes 0·5 as a typical value at stagnation point. Using this value, Mr. Graystone illustrated graphs showing the values of airspeed and ambient temperature at different pressure levels, such that the equilibrium surface temperature was 0°C. Graphs for 700 and 500 millibars are shown in Figure 1.

The presence of ice crystals in the cloud necessitates an additional term in the thermal balance equation: this is the latent heat required to melt the ice crystals on impact, and it reduces still further the effect of aerodynamic heating. The effect of this term is shown in Figure 1, where the two curves for 500 millibars show the difference between a water and an ice cloud, assuming the same rate of catch. For a mixed water–ice cloud, the curve would be intermediate.

Mr. Graystone emphasized that numerous assumptions and approximations were made in constructing these graphs, and that more observations of the occurrence and non-occurrence of icing on high-speed aircraft were needed. He indicated also the variability of the equilibrium temperature over the airframe. Evaporation cooling, for instance, would be greatest where the pressure was lowest, and some wind-tunnel experiments published by Coles[7] had shown icing to occur first behind the shoulder of a diamond-shaped aerofoil.

Another point on which observations were needed was the behaviour of a high-speed aircraft in ice-crystal clouds. These are normally safe as regards icing but, if an airframe is wet, it is possible for the ice-crystals to adhere. Hence light icing in cirrus cloud might occur in marginal conditions.

Mr. D. D. Clark, opening the general discussion spoke of experimental work at Farnborough on the subject of kinetic heating. Measurements of the recovery factor gave some exceptionally low values, when free-stream turbulence was artificially induced. Hence the expected temperature rise might not occur on parts of an aircraft subject to this type of turbulence. He mentioned also the possible hazard of clear-air icing on the upper wing surface of fast aircraft at low levels, where temperature reduction caused condensation. Mr. Graystone replied that he had used a recovery factor intermediate between the values, normally taken as 0·85 and 0·9, applicable to laminar and turbulent flow in the boundary layer.

In reply to a question by *Mr. Gold*, Mr. Graystone said that in equilibrium conditions the temperature variation over the surface of an aircraft was small but the time taken to reach equilibrium would vary for different aircraft and for different parts of the same aircraft.

Mr. T. L. Hunt confirmed that layer cloud, when formed by convection over the sea or orographic uplift, can give considerable icing.

Mr. Saxby thought that Mr. Crossley's histogram of icing frequency in cloud against temperature reflected the way in which the rapid growth of ice crystals depleted the cloud water content. Mr. Crossley agreed that the figures probably reflected a decrease of liquid water content with temperature but Mr. Jones stressed that in many clouds there would be too few ice crystals to have much effect in removing liquid water until temperatures were below about −15°C.

The discussion took a rather unexpected turn when the *Director-General* commented that the discussion was on "Icing", not merely icing on aircraft, and enquired what the feasibility was of issuing warnings of icy roads.

Mr. Veryard said that, although there was a Meteorological Office Order on the subject, there was still some uncertainty regarding the factors determining the formation of ice on roads.

Mr. Jacobs said that the Road Research Station is working on this; the nature of the road surface was important.

It was generally agreed that the forecasting of the temperature of the road surface presented some difficulty. *Dr. Sutcliffe*, however, was of the opinion that whenever the screen temperature fell below freezing point there would be patches of ice on many roads, and revealed a not altogether unexpected liking for living dangerously in contrast to the Director-General who would leave his car at home if ice was certainly forecast!

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NOTES AND NEWS

Observation of cumulonimbus top extending into the stratosphere

At 1500 G.M.T. on Monday 10 August 1959 the synoptic chart showed a slow-moving depression over north-east Belgium with troughs south-eastwards to Switzerland and westwards to the Bristol Channel. There was an area of active thunderstorms over north-east Belgium and the photograph facing page 50, taken over Bree (06481) at 1445 G.M.T., shows the top of a cumulonimbus at a true altitude of 42,500 feet. The Pilot (Flight Lieutenant Jackson) reported moderate turbulence at 100 feet above the top but smooth elsewhere.

With afternoon temperatures in the order of +28°C. (dry bulb) and +19°C. (dew-point), the 1200 G.M.T. ascent from Brussels gives instability to the tropopause at 38,500 feet (−56°C.) and a temperature at 42,500 feet of −53°C.

Heavy thunderstorms with rain were reported from Kleine Brogel (06479) at 1500 G.M.T., Geilenkirchen (10500) at 1712 G.M.T., Wildenrath (10402) at 1615 G.M.T. and 1725 G.M.T., and Bruggen (10401) at 1728, 1740 and 1800 G.M.T. with visibilities falling to 700–1,200 yards in heavy rain, and hail was reported at Wildenrath at 1610 G.M.T. Although the surface wind was mainly light, gusts to 40 knots were recorded in the thunderstorms at Bruggen.

Acknowledgments:—The author is indebted to Flight Lieutenants Jackson and Slattery for supplying the photograph and to Wing Commander Allen for permission to publish it.

P. MENMUIR

Kew Observatory sunshine records

Arising from comparisons between the amounts of sunshine recorded at Kew Observatory and at other stations in the London area during the years 1942–

1948, the sunshine cards for Kew Observatory have been re-measured and revised values have now been adopted as follows:

MONTHLY AND ANNUAL TOTALS OF SUNSHINE IN HOURS AT KEW OBSERVATORY, 1942–48

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
1942	33·8	36·2	72·8	216·0	230·2	252·7	175·9	158·9	126·9	86·1	55·9	54·0	1,499·4
1943	43·7	77·3	114·1	166·3	247·2	213·3	199·0	200·6	143·8	81·1	53·3	34·6	1,574·3
1944	30·7	55·0	100·5	136·3	226·9	187·0	107·3	199·3	142·8	80·7	50·6	40·9	1,358·0
1945	36·1	59·0	142·6	182·5	189·0	202·0	195·1	148·9	63·8	108·9	32·3	43·0	1,403·2
1946	51·4	67·5	84·0	198·9	190·9	169·2	238·5	158·6	116·1	77·0	39·4	50·0	1,441·5
1947	54·6	18·9	66·5	174·5	181·8	216·6	174·8	278·5	171·4	100·6	62·5	23·7	1,524·4
1948	42·8	73·6	139·7	224·7	237·2	179·1	184·5	152·0	159·0	92·3	69·9	45·0	1,600·2

REVISED AVERAGE VALUES OF SUNSHINE IN HOURS FOR THE PERIOD 1921–50

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Daily mean	1·38	2·15	3·63	4·98	6·32	7·02	6·41	6·04	4·67	3·11	1·72	1·29	4·07
Monthly total	43	61	113	149	196	210	199	187	140	96	52	40	1,486

These revised figures affect those previously published in the *Monthly Weather Report*, *A Century of London Weather*, *Averages of Bright Sunshine for Great Britain and Northern Ireland 1921–50*, and elsewhere. It is hoped to include a complete list of corrections to the *Monthly Weather Report* in the Introduction to the report for 1959, due to be issued in the summer of 1960.

OBITUARY

C. T. R. Wilson, C.H., F.R.S., Nobel Laureate

With the death on 16 November 1959, at the age of 90, of Prof. C. T. R. Wilson, meteorology may be said to have lost the father of cloud physics. Wilson's interest in cloud phenomena started in 1894 when as a young physics graduate from the Cavendish Laboratory he spent a few weeks as relief meteorological observer at the Ben Nevis Observatory. In a vivid account of his experiences there written 60 years later[1] he said that "the whole of my scientific work undoubtedly developed from the experiments I was led to make by what I saw during my fortnight at Ben Nevis in September 1894". On his return to Cambridge he began his experiments to produce an artificial cloud by the expansion of moist air. It was these experiments that led to his development of the cloud chamber which has played such an important part in atomic and nuclear physics.

Wilson's observations in a violent thunderstorm on another Scottish peak led him to devote much of his time to investigating the atmospheric electrical field and the mechanism of a thunder cloud. One outcome of this was his well known theory of the capture of ions by falling drops. Another was the hypothesis, now generally accepted, that thunderstorms and shower clouds act as generators that maintain the fair-weather atmospheric electrical field.

Wilson was not a prolific writer but nearly all his published papers were written with great clarity. His article on atmospheric electricity in the *Dictionary of applied physics* published in 1923 remained for many years the best survey of the subject. Although he could hardly be described as a very good lecturer he was an excellent teacher in the experimental physics laboratory and the writer is glad to acknowledge the help and encouragement he received from

C. T. R. not only as a student in the Cavendish Laboratory, but also in later years when undertaking atmospheric electrical research in the Meteorological Office.

Wilson's great interest in cloud physics continued to the end of his long life, for it was during his last five years that he seized every opportunity of observing clouds from the air by joining meteorological students from Edinburgh University in aircraft flights arranged for them by the Royal Air Force. Indeed, the fact that some of the flights around cumulonimbus clouds were uncomfortably bumpy, especially for a man nearing 90, seems to have added to his enthusiasm.

Practically the whole of Wilson's working life was spent at Cambridge, first as University lecturer in experimental physics and then from 1928 to 1936 as Jacksonian Professor of Natural Philosophy. He shared the Nobel Prize for Physics with A. H. Compton in 1927.

REFERENCE

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F. J. SCRASE

METEOROLOGICAL OFFICE NEWS

Retirements.—The Director-General records his appreciation of the service of:—

Mr. F. W. Jude, M.B.E., Senior Experimental Officer, who retired on 31 December 1959. He joined the Office in July 1920 as a Technical Assistant, after service during the First World War in the Rifle Brigade and the Cyclists Corps. Apart from a period from 1925 to 1931 at Headquarters in the Aviation Services Division, practically the whole of his service has been spent at aviation outstations, including two tours of duty overseas in the Middle East and Iraq. From 1952 until his retirement he served at Oakington. He was appointed a Member of the Most Excellent Order of the British Empire (Military Division) in the New Year Honours List of 1946.

OFFICIAL PUBLICATION

The following publication has recently been issued:

PROFESSIONAL NOTES

No. 125—*Averages of accumulated temperature and standard deviation of monthly mean temperature over Britain, 1921–50.* By H. C. Shellard, B.Sc.

Using a method of computing long-term averages of accumulated temperature (sometimes referred to as normal degree-days) due to H. C. S. Thom, average values with respect to various base temperatures are presented for 49 stations in the United Kingdom for the period 1921–50. Monthly and annual averages accumulated below base temperatures of 70°F., 60°F., 50°F. and 42°F. and above base temperatures of 42°F. and 60°F. are given. Maps of annual accumulated temperature below 60°F., based on 162 stations, are included, one based on station values, the other on values reduced to mean sea level. A method is described for estimating averages of an accumulated temperature below 60°F. for any place given its position, height, estimates of monthly averages of daily mean temperature and of the standard deviations of its monthly mean temperatures. The monthly averages may be interpolated from maps already published elsewhere and the standard deviations from monthly maps presented in Part 2 of the Note. These maps are based on computed standard deviations of monthly mean temperatures for the period 1921–50 for 52 stations in the British Isles.

REVIEWS

Realisation du Centre de Physique du Globe à Dourbes. By E. Lahaye. 12 in × 9 in., pp. 104, *illus.* Institut Royal Météorologique de Belgique, Avenue Circulaire, 3, Uccle-Bruxelles 18. 1958.

Observatories last a long time and those who plan them must seek a site likely to be unaffected by man-made disturbances. Our own observatory at Kew has retained its immediate park-like surroundings for the nearly 200 years of its existence, but the arrival of electric transport early in this century necessitated the removal of magnetic recording to the remote observatory of Eskdalemuir. For the same reason the magnetic work of the Royal Greenwich Observatory was transferred first to Abinger and recently to the rural site of Hartland in Devonshire.

The Belgian magnetic observatory at Uccle has similarly been affected by the growth of nearby Brussels. M. Edm. Lahaye, Director of the Royal Meteorological Institute of Belgium and author of the present publication, announced at the Oslo UGGI meeting in 1948 that a site for a new geophysical observatory had been selected at Dourbes (50°5′N, 4°36′E) in open countryside some 55 miles south of Brussels. Those present at the Brussels UGGI meeting in 1951 were able to go on an outing to see the satisfactory progress made at Dourbes, where magnetic recording started shortly afterwards—in March 1952.

The seven chapters of the present publication illustrated by 114 photographs, 14 of which are coloured, and 14 maps or plans, describe the search for the site, the layout and purpose of the various "pavilions" which, apart from the three-storied central laboratory and office building, are mostly single-storied and well separated (the site area is about 130 acres) and the equipment installed. The latter is lavish, very modern and mostly continuously recording and, particularly in the absolute magnetic measurements section, includes instruments specially designed by the staff, of which we are promised more details in another publication.

The wide range of geophysical studies covers the earth's magnetic field, earth currents, atmospheric electricity, ionospheric structure, "sferics" and tropospheric propagation, spectroscopy of the night sky (and of any auroras) meteorology including radiation, atmospheric chemistry, radioactive content of the air and of precipitation, cosmic rays and seismology.

This brief statement can only indicate the amount of thought and care that has gone into the planning of Dourbes, which was officially opened on 25 June 1956 and those who require full details are recommended to study the present publication. We wish our Belgian colleagues every success in their work at the magnificent new observatory at Dourbes.

L. JACOBS

Weather and climate. By Clarence E. Koeppe and George C. de Long. 10 in. × 7 in., pp. viii+341, *illus.*, McGraw-Hill Publishing Co. Ltd., 95 Farringdon Street, London, E.C.4, 1958. Price: 58*s*.

Whether in the higher forms of schools, or perhaps in their first year at the university, students of geography require texts on weather and climate. Numerous works attempt to satisfy this need, especially taking account of the many "arts" entrants. There must be beginnings, even if readers of this Magazine may dispute their adequacy as a basis for a meteorologist's education. Descriptive accounts of the distribution of phenomena are not likely to lead far, unless the student gains knowledge from observation and measurement of the nature of the substances he is dealing with.

None the less, a demand exists on the part of many who are not going to be professional meteorologists. The work under notice, addressed to college students in America, is a sufficiently commendable example of its kind: it makes a good "packaged deal". The first half is elementary descriptive meteorology; the second is geographical climatology with plenty of reference to Köppen. The presentation is efficient, readable, shiny, double-column, well illustrated and indexed. The "arts geographer" and many general readers on that continent will find, within limits, a satisfactory assemblage of most of the things one has learnt to expect. Mathematical expression is strenously avoided; physics is kept, with much ingenuity, to a quite remarkable minimum, even in the rather surprising chapter on atmospheric optics. Warm-core highs, jet streams and mountain waves are briefly mentioned but with little explanation or further reference. A short chapter on weather lore makes a welcome adornment.

It is characteristic of books of this type that there are phrases to give the meteorologist pause (p. 8, "Vertical or nearly vertical movements of air . . . should be referred to as air currents"; p. 126, "although air moves down the isobaric slope, it can move at a deflection of as much as 90° to the slope"; p. 197, "such charts are called isopleths"; p. 261, "cyclones gravitate to these areas"). That (p. 25) "the weight of the atmosphere is 5½ quintillion tons" is truly astounding. A photograph of a halo (p. 141) is ascribed to "G. A. Clarke, U.S. Weather Bureau" and on p. 142 the familiar Aberdeen roofs appear again ("U.S. Weather Bureau").

The text is primarily addressed to American readers; only United States weather maps and instruments are illustrated. We find inches and grains per cubic foot as well as millibars and gram-calories; on p. 33 metres and inches are used separately for wavelengths. Clarity of writing, abundance of illustrations and some good maps should appeal to the industrious collector of facts and could serve the needs of English sixth-formers. There is a fairly general bibliography in which several favourite English texts appear under their American publishers. No mention is made of journals from countries other than the United States of America.

The geography is generally pleasant; it is agreeable to find some stress on the relationships of climate, soil and natural vegetation. Some temperature and rainfall data are assembled after the manner of Kendrew. Some of the Siberian stations are unfamiliar; comments on the cold of February 1956 in Europe are up to date; that Britain and Western Europe experience considerable radiation fog should be mentioned. Geographers will not be happy to find the Etesians confused with the Vardarak (p. 137), the tramontana ascribed to Central Europe (p. 138) and lack of reference to the southern hemisphere (p 118). Although the Hobbsian anticyclone is agreeably banished, humanists will be troubled (p. 300) to read that "Eskimos dwell seasonally on the ice-cap in some cases".

A beautifully printed map of Climatic Regions of the World, on the system of one of the authors (Koeppe), is placed beside the more familiar and more rigorous Köppen–Geiger map and makes for interesting comparison. Newfoundland, for example, seems to be wrongly allocated and the ascription of Tibet begs the question; the distinction of a "marine subpolar" type is attractive.

In all, a compact, pleasant, and reasonably satisfactory textbook within the clearly defined limits set by the authors. But its very high price makes it far too expensive for the majority of English schools. Some university students will probably find it attractive for general reading. The present reviewer feels that in Britain the serious Honours student, even in the Faculty of Arts, will appreciate the summary of the Köppen regions and the maps but in other respects will find the simplifications irksome and be led to prefer a more rigorous treatment such as the prospective meteorologist will in any event demand.

G. MANLEY

WEATHER OF OCTOBER 1959

Northern Hemisphere

The most anomalous feature of the mean pressure chart was the Iceland low which, although centred in its usual position, was 14 millibars deeper than usual. An associated area of negative pressure anomaly extended over Greenland, eastern Canada and much of the North Atlantic. A further low-pressure area was centred over north-west Russia giving anomalies of −8 millibars over the Urals. Over Europe west of 30°E. pressure anomalies were positive: they were only +2 or +3 millibars over central Europe but rose to +5 millibars in the north of Scandinavia. Anomalies were also positive along the north coast of Russia and in the Siberian Arctic with maximum values of +8 millibars just south of Severnaya Zemlya and in the extreme north-east of Asia. The Siberian high was slightly weaker than usual. There were no large departures from normal pressure over North America. The Aleutian low was of approximately normal intensity but centred south-west of its usual position giving anomalies of −7 millibars between 40°N. and 50°N. over the central Pacific.

Mean temperatures were above average over Europe north-west of a line approximately from the Straits of Gibraltar to the east coast of the Baltic, largely as a result of persistent southerly winds in the first half of the month. Anomalies were greatest over the British Isles, the Faeroes, Jan Mayen and Spitsbergen, reaching +3°C. in all these areas. It was a particularly cool month in Turkey and Greece where anomalies were −4°C. at many stations. Over much of North America including almost all of Canada and central districts of the United States of America temperatures were below average, anomalies being −3°C. and −4°C. at many places in the centre of the Continent. It was reported on the 12th that unseasonably early snow had covered central Canada to a depth of three feet.

The precipitation pattern over Europe was rather complex. Totals were generally slightly above average over Britain, apart from eastern districts of England, France (except the north-east), Spain and southern Sweden, but below average over the Low Countries and much of Germany and south-east Europe. During the last week of the month four days of heavy rain caused extensive flood damage in the Po valley in Italy and landslides in the mountains. Rainfall amounts over North America were above normal nearly everywhere, and amounts at some places in south-eastern states of the United States were between two and three times the average. In the first week of the month serious floods were reported in Oklahoma following heavy and widespread rain. Rainfall totals for the month were up to five times the average in the north-east of India and east Pakistan. Much of the rain was associated with one particular cyclone and fell during a period of about four days, producing extensive flooding in west Bengal.

WEATHER OF NOVEMBER 1959

Great Britain and Northern Ireland

The month was generally unsettled with some cold foggy periods during the first half, but during the second half weather was mild with heavy rain at times. Under the influence of an anticyclone to the south-west of the country rainfall was comparatively light during the first week. After two mild days with afternoon temperatures reading 60°F. in places, cold northerly winds brought showers to most districts with some sleet or snow in the north and west. Winds became light and variable on the 5th, and that evening fog and frost became fairly widespread in England and Wales; the fog was dense locally during the next two nights and persisted all day in some industrial areas.

Rain, with wind reaching gale force at times, associated with a vigorous depression near Iceland, spread across the country on the 8th and 9th and was followed on the 10th by squally showers with hail and thunder locally and some sleet or snow in the north and west; on the 8th some places had more than two inches of rain in 24 hours. Fog and frost again became widespread on the night of the 11th–12th, screen temperature falling as low as 19°F. at Gatwick, Birmingham and Aberdeen. The fog persisted throughout the following day in parts of eastern England with temperatures remaining below freezing point.

Strong winds and heavy rain cleared the fog before dawn on the 13th as a vigorous depression moved across Eire to become centred over southern England during the next two days; a gust of 91 knots was recorded at the Lizard on the 13th and places in Pembrokeshire had over three inches of rain in 24 hours on both the 14th and 15th. As the depression filled up winds became light and on the 16th fog returned to much of England and became thicker and more persistent the next day.

A depression from the Bay of Biscay brought heavy rain to southern England on the 17th and 18th; rain spread northward to the whole country on the 18th, but there was snow at first in parts of Scotland where high winds caused drifts which blocked many roads. The southerly winds brought dull but mild weather, with temperatures between 50°F. and 60°F., to all districts; this lasted until the 24th. A belt of rain associated with a cold front reached western Ireland late on the 24th and moved steadily eastward clearing the east coast of England about 36 hours later. Substantial amounts fell in many parts of the country, more than three inches being recorded in the 24 hours in parts of South Wales and Devonshire. The remainder of the month was mainly cloudy with periods of rain nearly everywhere.

Taking the month as a whole, temperature was slightly above average, but the second half was considerably milder than the first. Sunshine amounts were very variable, being mainly above average over much of southern and north-western England and below average in parts of the Midlands and Yorkshire. Rainfall was 127 per cent of the average over England and Wales, 141 per cent over Scotland and 108 per cent over Northern Ireland. Over the United Kingdom as a whole it was the wettest November since 1954, but for England and Wales the total rainfall for the year up to the end of November was the lowest since 1921.

The first frosts of the season largely rid brassica crops of aphis and white fly (spring cabbage were looking very healthy), caused a rush to get dahlia tubers lifted and finished off chrysanthemums in bloom in many unheated houses. The heavy rains softened the ground to a considerable depth and nurserymen were able to proceed with their autumn planting.

WEATHER OF DECEMBER 1959

The general character of the weather is shown by the following provisional figures:—

	AIR TEMPERATURE			RAINFALL		SUNSHINE
	Highest	Lowest	Difference from average daily mean†	Per-centage of average*	No. of days difference from average*	Per-centage of average†
	°F.	°F.	°F.	%		%
England and Wales ...	59	22	+2·5	181	+7	74
Scotland	57	19	+0·9	141	+4	68
Northern Ireland ...	54	25	+0·4	132	+4	100

* 1916–1950 † 1921–1950

RAINFALL OF DECEMBER 1959

Great Britain and Northern Ireland

County	Station	In.	*Per cent of Av.	County	Station	In.	*Per cent of Av.
London	Camden Square ...	3·35	152	*Pemb.*	Maenclochog, Dolwen Br.	11·01	159
Kent	Dover	7·17	246	*Cards.*	Aberporth	5·86	131
„	Edenbridge, Falconhurst	6·86	213	*Radnor*	Llandrindod Wells ...	7·92	182
Sussex	Compton, Compton Ho.	9·62	237	*Mont.*	Lake Vyrnwy	13·99	195
„	Worthing, Beach Ho. Pk.	6·28	217	*Mer.*	Blaenau Festiniog ...	21·27	186
Hants.	St. Catherine's L'thouse	...	...	„	Aberdovey	6·75	161
„	Southampton, East Pk.	6·46	191	*Carn.*	Llandudno	4·46	153
„	South Farnborough ...	4·50	166	*Angl.*	Llanerchymedd ...	6·00	140
Herts.	Harpenden, Rothamsted	4·43	176	*I. Man*	Douglas, Borough Cem.	9·99	205
Bucks.	Slough, Upton	3·59	159	*Wigtown*	Newtown Stewart ...	8·38	164
Oxford	Oxford, Radcliffe ...	4·88	214	*Dumf.*	Dumfries, Crichton R.I.	7·25	169
N'hants.	Wellingboro' Swanspool	4·11	194	„	Eskdalemuir Obsy. ...	9·21	147
Essex	Southend W.W. ...	2·61	138	*Roxb.*	Crailing	3·12	158
Suffolk	Ipswich, Belstead Hall	3·30	148	*Peebles*	Stobo Castle	5·75	153
„	Lowestoft Sec. School ...	2·88	131	*Berwick*	Marchmont House ...	3·25	138
„	Bury St. Ed., Westley H.	3·21	147	*E. Loth.*	N. Berwick	3·17	174
Norfolk	Sandringham Ho. Gdns.	4·76	206	*Midl'n.*	Edinburgh, Blackf'd H.	2·74	130
Dorset	Creech Grange ...	8·63	198	*Lanark*	Hamilton W.W., T'nhill	5·00	127
„	Beaminster, East St. ...	11·05	241	*Ayr*	Prestwick	4·26	114
Devon	Teignmouth, Den Gdns.	6·65	173	„	Glen Afton, Ayr San. ...	9·40	142
„	Ilfracombe	8·65	197	*Renfrew*	Greenock, Prospect Hill	10·63	152
„	Princetown	19·49	190	*Bute*	Rothesay	9·29	157
Cornwall	Bude	7·22	189	*Argyll*	Morven, Drimnin ...	9·78	145
„	Penzance	10·26	212	„	Ardrishaig, Canal Office	10·24	137
„	St. Austell	9·45	168	„	Inveraray Castle ...	14·38	157
„	Scilly, St. Marys ...	8·29	235	„	Islay, Eallabus	9·61	162
Somerset	Bath	6·45	220	„	Tiree	6·89	148
„	Taunton	6·43	208	*Kinross*	Loch Leven Sluice ...	5·61	173
Glos.	Cirencester	6·57	211	*Fife*	Leuchars Airfield ...	5·01	233
Salop	Church Stretton ...	6·52	195	*Perth*	Loch Dhu	15·06	164
„	Shrewsbury, Monkmore	4·19	190	„	Crieff, Strathearn Hyd.	6·91	166
Worcs.	Worcester, Red Hill ...	4·22	197	„	Pitlochry, Fincastle ...	6·61	176
Warwick	Birmingham, Edgbaston	5·15	190	*Angus*	Montrose Hospital ...	5·07	205
Leics.	Thornton Reservoir ...	3·92	162	*Aberd.*	Braemar	6·18	164
Lincs.	Cranwell Airfield ...	2·71	142	„	Dyce, Craibstone ...	4·50	142
„	Skegness, Marine Gdns.	4·59	228	„	New Deer School House	3·85	126
Notts.	Mansfield, Carr Bank ...	4·21	172	*Moray*	Gordon Castle	2·06	92
Derby	Buxton, Terrace Slopes	8·98	186	*Inverness*	Loch Ness, Garthbeg ...	4·40	109
Ches.	Bidston Observatory ...	4·25	162	„	Fort William	11·99	138
„	Manchester, Airport ...	4·72	172	„	Sky, Duntulm	8·55	153
Lancs.	Stonyhurst College ...	6·97	157	„	Benbecula	...	...
„	Squires Gate	6·11	194	*R. & C.*	Fearn, Geanies ...	1·15	63
Yorks.	Wakefield, Clarence Pk.	3·06	153	„	Inverbroom, Glackour...	6·27	107
„	Hull, Pearson Park ...	3·16	140	„	Loch Duich, Ratagan ...	9·59	109
„	Felixkirk, Mt. St. John	3·65	145	„	Achnashellach	9·41	109
„	York Museum	3·04	150	„	Stornoway	5·35	132
„	Scarborough	3·21	130	*Caith.*	Wick Airfield	3·14	106
„	Middlesbrough ...	2·48	127	*Shetland*	Lerwick Observatory ...	7·26	164
„	Baldersdale, Hury Res.	6·70	191	*Ferm.*	Belleek	5·76	117
Nor'l'd	Newcastle, Leazes Pk. ...	2·94	119	*Armagh*	Armagh Observatory ...	4·57	146
„	Bellingham, High Green	4·80	161	*Down*	Seaforde	5·60	126
„	Lilburn Tower Gdns. ...	4·80	176	*Antrim*	Aldergrove Airfield ...	5·27	149
Cumb.	Geltsdale	5·18	165	„	Ballymena, Harryville ...	6·74	154
„	Keswick, Derwent Island	10·65	174	*L'derry*	Garvagh, Moneydig ...	5·21	119
„	Ravenglass, The Grove	7·47	167	„	Londonderry, Creggan	4·21	92
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