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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:

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

*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

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

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:

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

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:

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

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

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

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

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, $Z_{0\cdot9}$, 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

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

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,

$$V_0 = k D_r^{0.31} \quad \ldots\ldots \quad (10)$$

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 $Z_{0.9}$. 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 $(1 + 0.21\,\mathrm{Re}^{\frac{1}{2}})$.

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, $Z_{0\cdot9}$ 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 $Z_{0\cdot9}$ have been calculated for values of $D_r = 0.5, 1\cdot0, 2\cdot0, 3\cdot0, 4\cdot0$ mm when γ is the saturated-adiabatic lapse rate, γ_s. They are marked in Figure 1 by small open circles. The relationship between $Z_{0\cdot9}$ and D_r is seen to be very nearly linear and, denoting $Z_{0\cdot9}$ by $Z_{0\cdot9}^{(s)}$ when $\gamma = \gamma_s$, the equations to the best-fitting straight lines are:

$$Z_{0\cdot9}^{(s)} = 79\cdot6\, D_r + 69\cdot0 \text{ (spheres)} \quad \ldots\ldots \quad (11)$$

$$Z_{0\cdot9}^{(s)} = 119\cdot7\, D_r + 102\cdot5 \text{ (disks)} \quad \ldots\ldots \quad (12)$$

where $Z_{0\cdot9}^{(s)}$ 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 $Z_{0\cdot9}^{(s)}$ 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 $Z_{0\cdot9}^{(s)}$ for real snowflakes since $\varphi(F)$ is unknown. However, from a study of the shape and structure of falling snow-flakes based

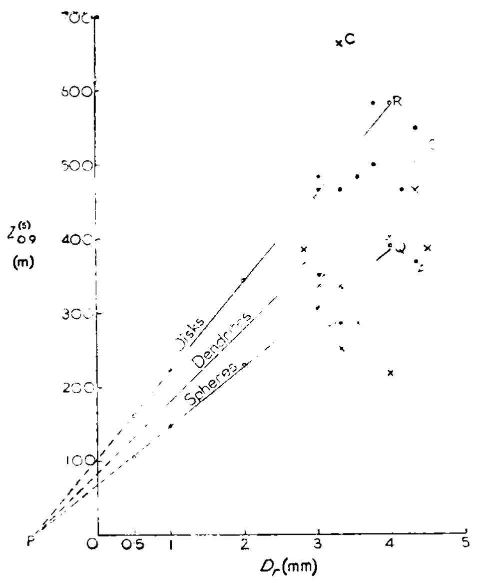

FIGURE 1—RELATIONSHIP BETWEEN THE MELTED DROP DIAMETER (D_r) OF A SNOW-FLAKE AND THE DISTANCE $(Z^{(s)}_{0.9})$ BELOW THE 0°C LEVEL AT WHICH IT IS 90 PER CENT MELTED IN A SATURATED ATMOSPHERE WITH A SATURATED-ADIABATIC LAPSE RATE.

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 $Z^{(s)}_{0.9}$ 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, $Z^{(s)}_{0.9}$ bears a constant ratio to $Z^{(s)}_{0.9}$ for spheres. Hence the relation between $Z^{(s)}_{0.9}$ 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

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

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:

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

whence we get, to a sufficient degree of accuracy,

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

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.

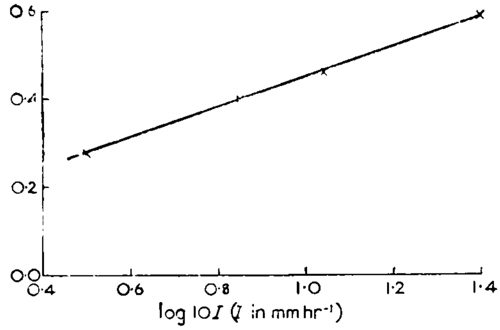

FIGURE 2—RELATION BETWEEN LARGEST MELTED-DROP DIAMETERS ($\log D_r^*$ IN MM) AND THE INTENSITY OF PRECIPITATION ($\log 10\, I$)

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 0·5°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).

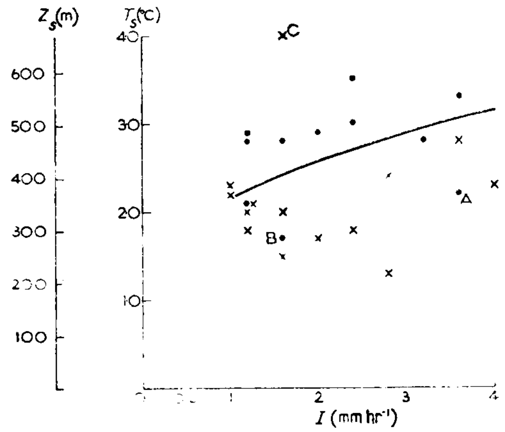

FIGURE 3—RELATION BETWEEN DEPTH OF PENETRATION OF SNOW AND THE INTENSITY OF MODERATE PRECIPITATION

(*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

$$Z^{(s)}_{0.9} = 96.5\, D_r + 84.0 \qquad \ldots\ldots \quad (18)$$

whence from equation (17)

$$T_s = 1.64\, I^{0.34} + 0.50 \qquad \ldots\ldots \quad (19)$$

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

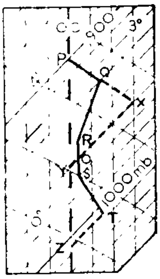

FIGURE 4—TEPHIGRAM SHOWING WET-BULB TEMPERATURE AT DOWNHAM MARKET AT 1500 GMT, 31 JANUARY 1950

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

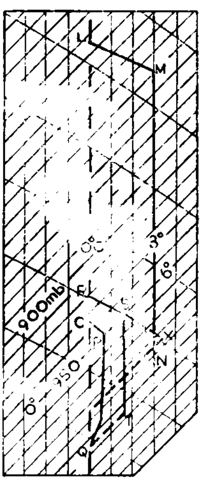

FIGURE 5—TEPHIGRAM SHOWING WET-BULB TEMPERATURE AT 0300 GMT, 19 DECEMBER 1952

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.

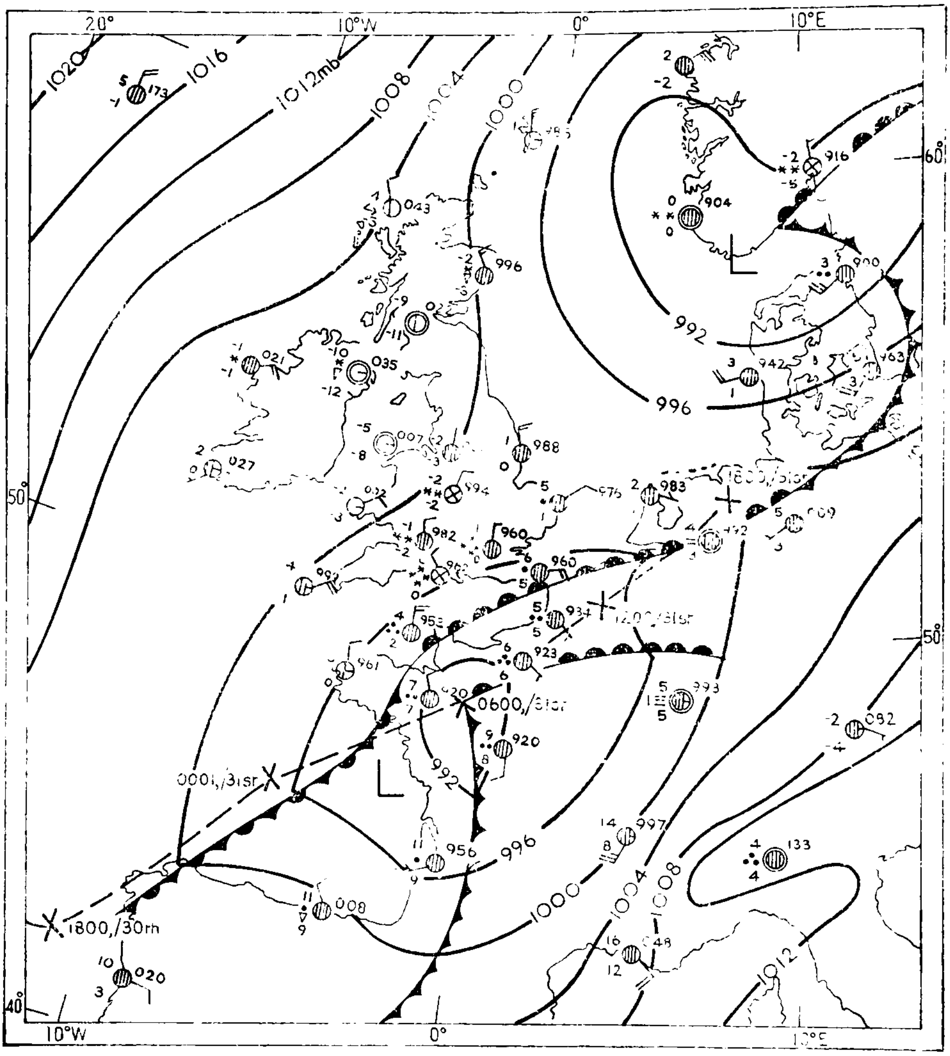

FIGURE 6—SYNOPTIC CHART FOR 0600 GMT, 31 DECEMBER 1961

— — — 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-

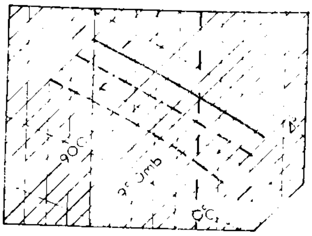

FIGURE 7—TEPHIGRAM FOR HEMSBY, 2330 GMT, 30 DECEMBER 1961
—— dry-bulb temperature
– – –– dew-point temperature
–·–·– wet-bulb temperature

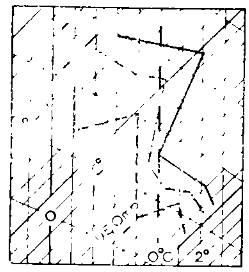

FIGURE 8—TEPHIGRAM FOR CRAWLEY, 2330 GMT, 30 DECEMBER 1961
—— dry-bulb temperature
– dew-point temperature
- · -- wet-bulb temperature
(Curves are extrapolated below 980 mb)

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 $T_s = 3 \cdot 0$°C) and on seven occasions exceeded 700 m (corresponding to $T_s = 4 \cdot 2$°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

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*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.

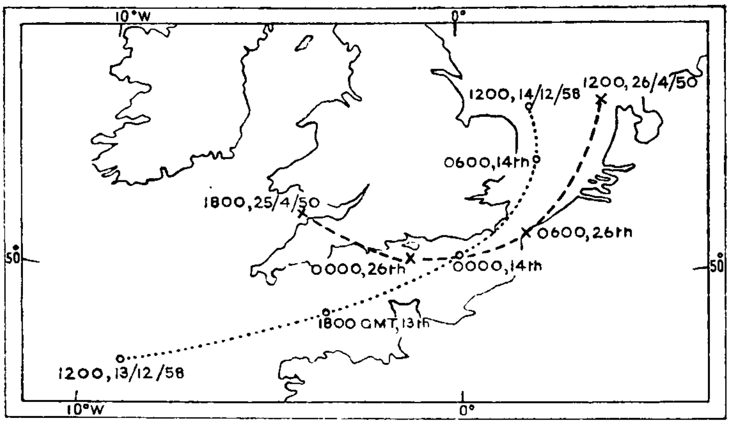

FIGURE 9 —TRACKS OF TWO POLAR LOWS

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

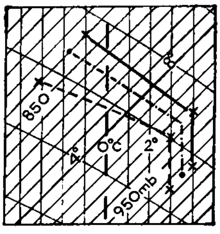

FIGURE 10—TEPHIGRAM FOR CRAWLEY, 2300 GMT, 13 DECEMBER 1958

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

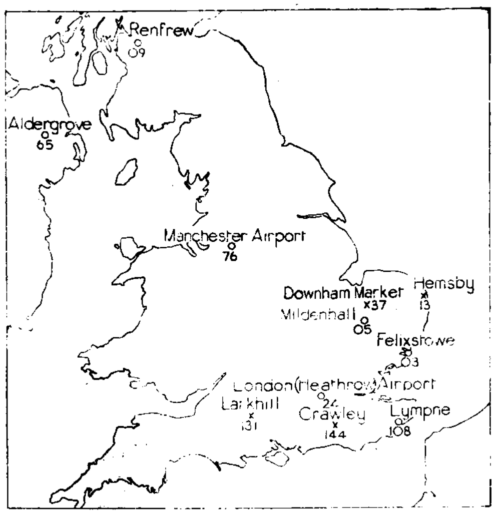

FIGURE 11—STATIONS FROM WHICH OBSERVATIONS HAVE BEEN USED
o surface observations.
x upper air observations.
The numbers indicate altitude in metres.

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.

Acknowledgements.—The author is indebted to Mr. J. C. Cumming, Chief Meteorological Officer, London (Heathrow) Airport and to Mr. G. M. Band, Meteorological Officer, Manchester Airport for supplying data of occasions of rain, sleet and snow.

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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.

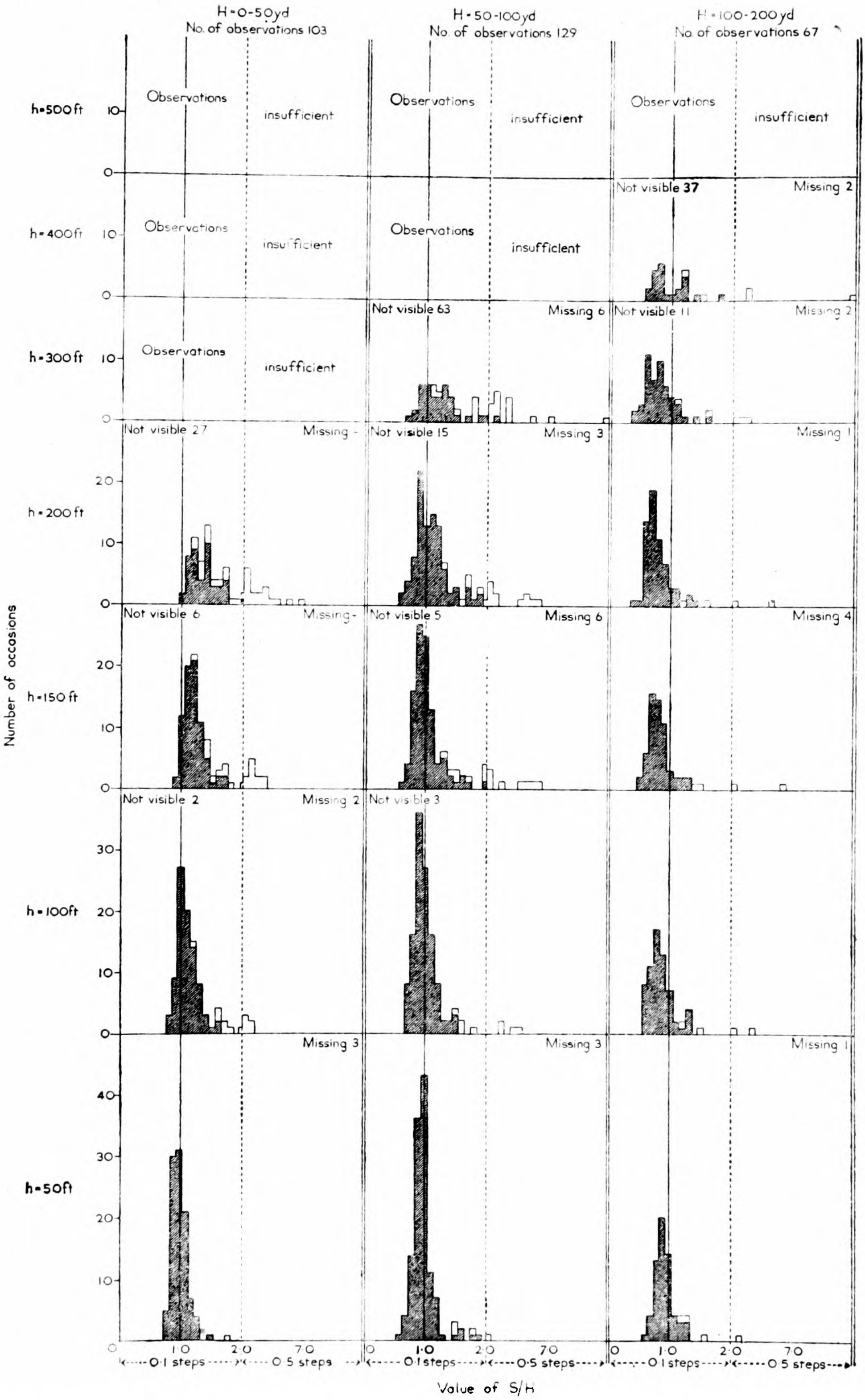

FIGURE I — HISTOGRAMS SHOWING FREQUENCY OF VARIOUS VALUES OF THE RATIO S/H

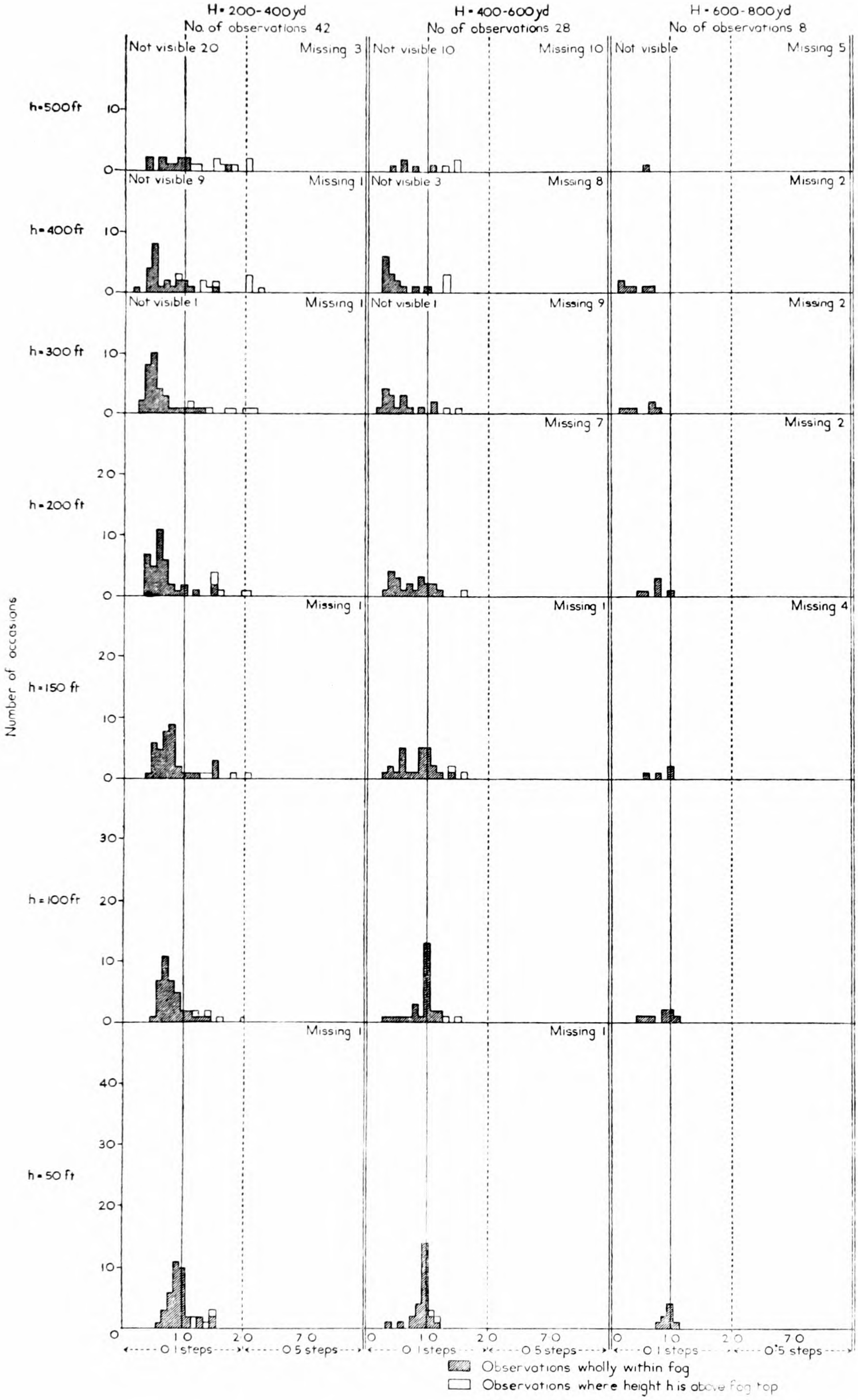

FIGURE I—(*cont.*)

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

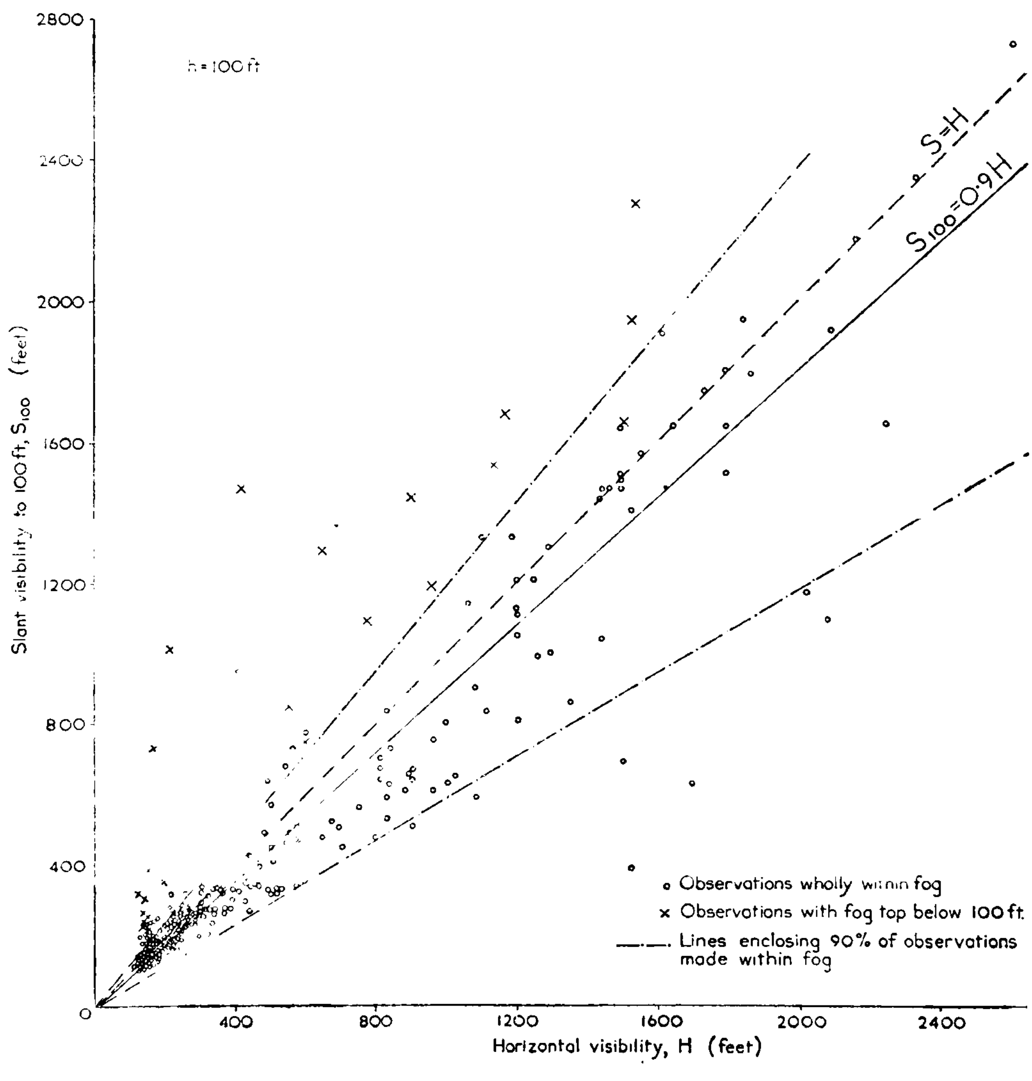

FIGURE 2 — PLOT OF SLANT VISIBILITY TO 100 FT AGAINST HORIZONTAL VISIBILITY

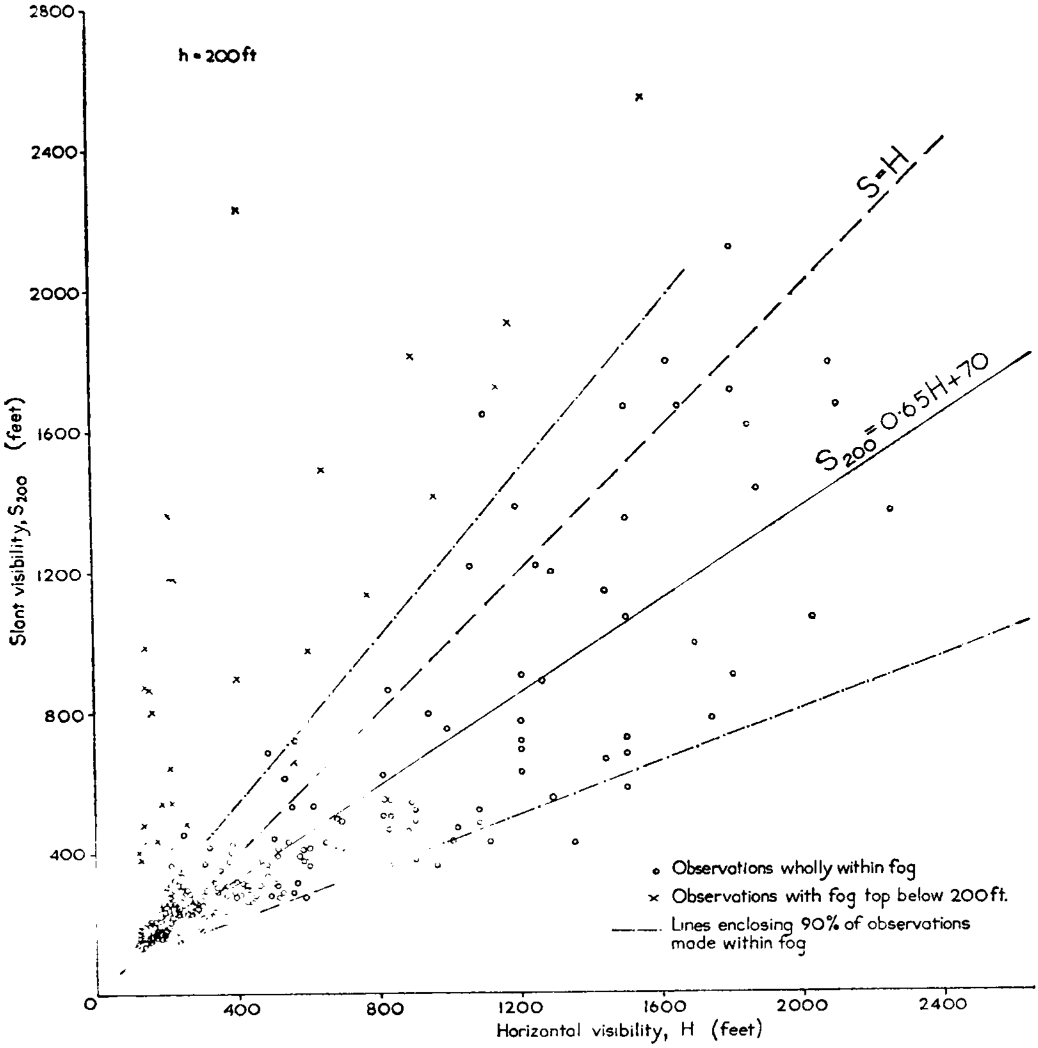

FIGURE 3 — PLOT OF SLANT VISIBILITY TO 200 FT AGAINST HORIZONTAL VISIBILITY

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.

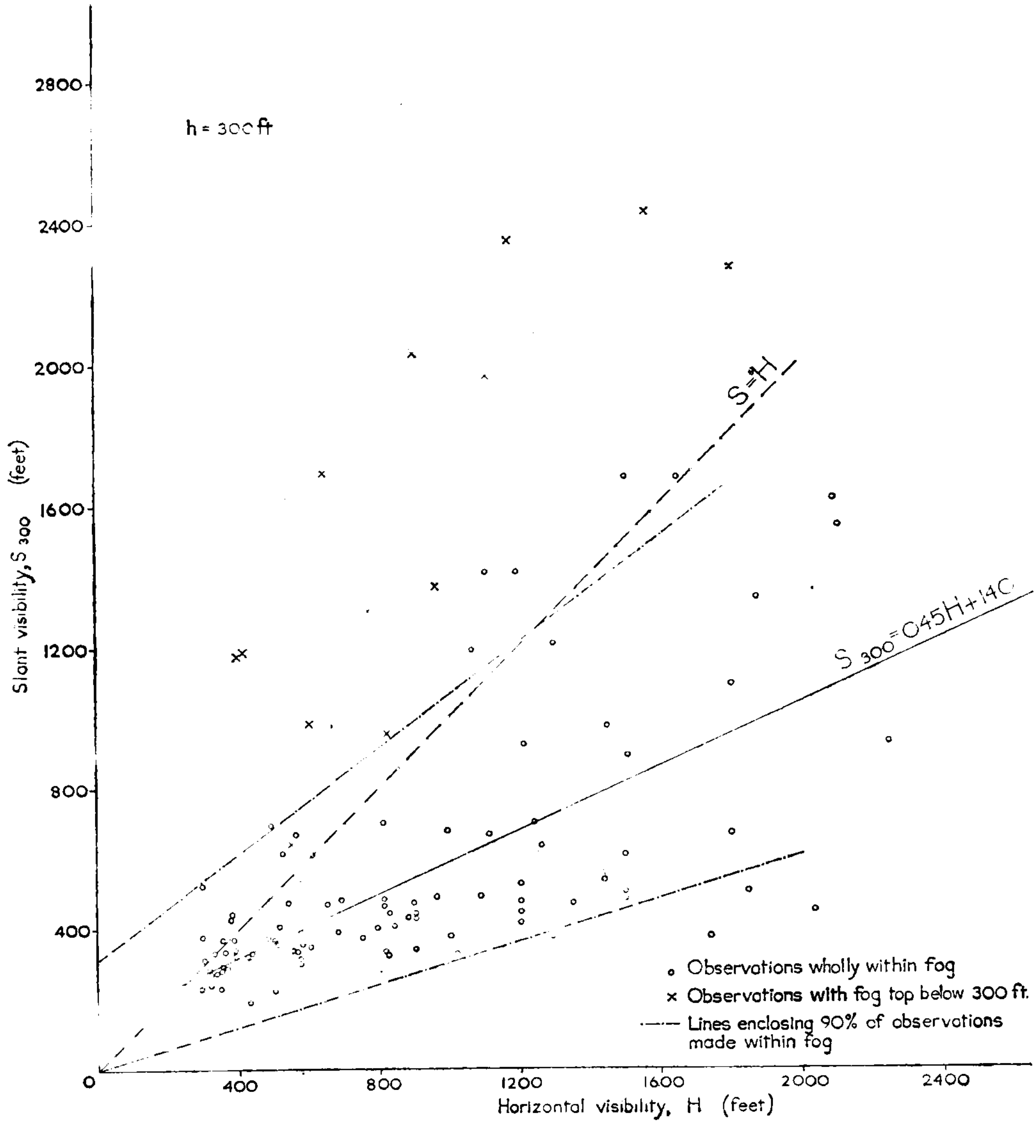

FIGURE 4 — PLOT OF SLANT VISIBILITY TO 300 FT AGAINST HORIZONTAL VISIBILITY

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 $A = 1.15 \times 10^{-6}$ (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.

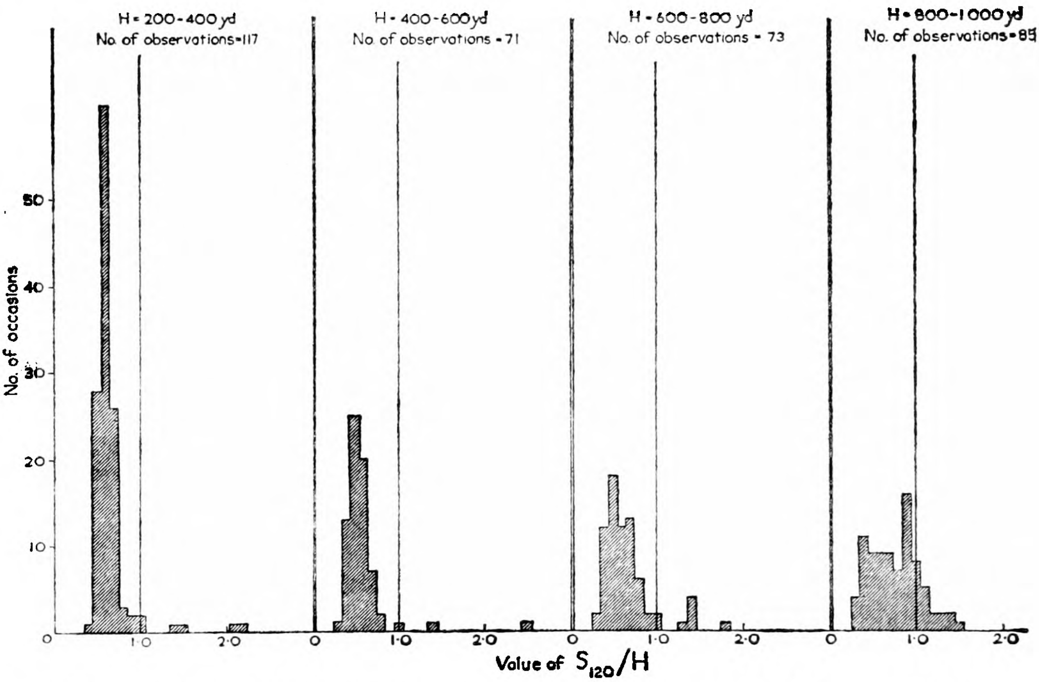

FIGURE 5 — FREQUENCY OF VARIOUS VALUES OF THE RATIO S_{120}/H IN A RESTRICTED CLASS OF FOG

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.

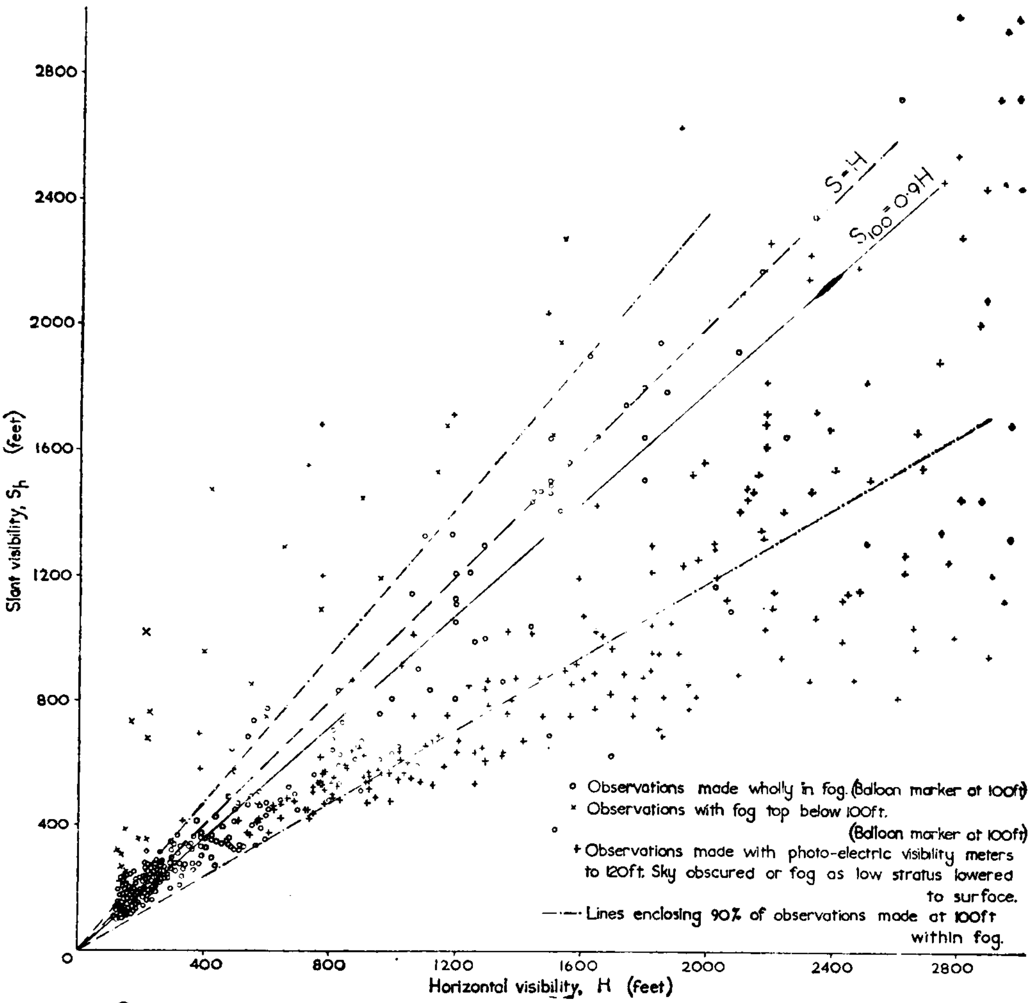

FIGURE 6 — OBSERVATIONS OF SLANT VISIBILITY MADE BY PHOTO-ELECTRIC METHODS, SUPERIMPOSED ON FIGURE 2

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.

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551.575.36:551.591.6

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.

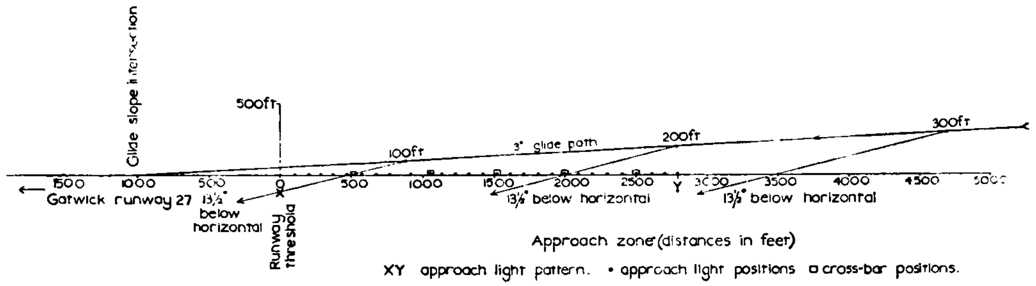

FIGURE 1 — RELATIONSHIP BETWEEN RUNWAY, APPROACH LIGHT PATTERN AND 3° GLIDE PATH FOR RUNWAY 27 AT GATWICK

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 ½° until between 2500 and 3000 ft from the threshold the beam of each light is 6½° 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.

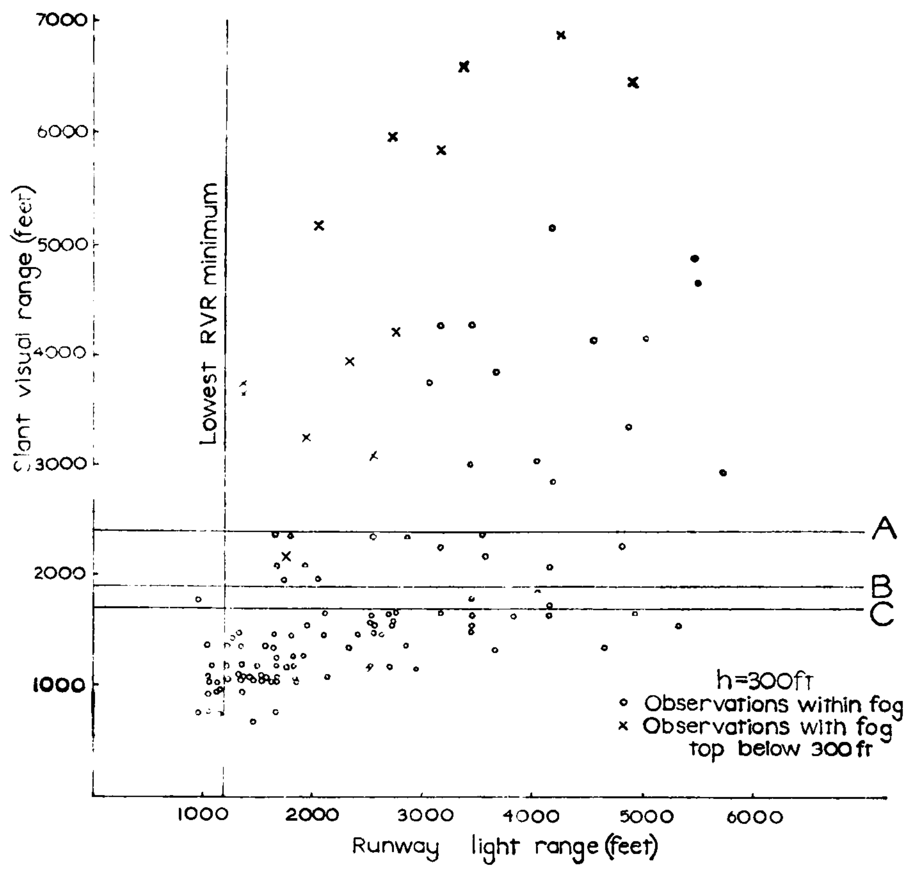

FIGURE 2 (*a*)

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.

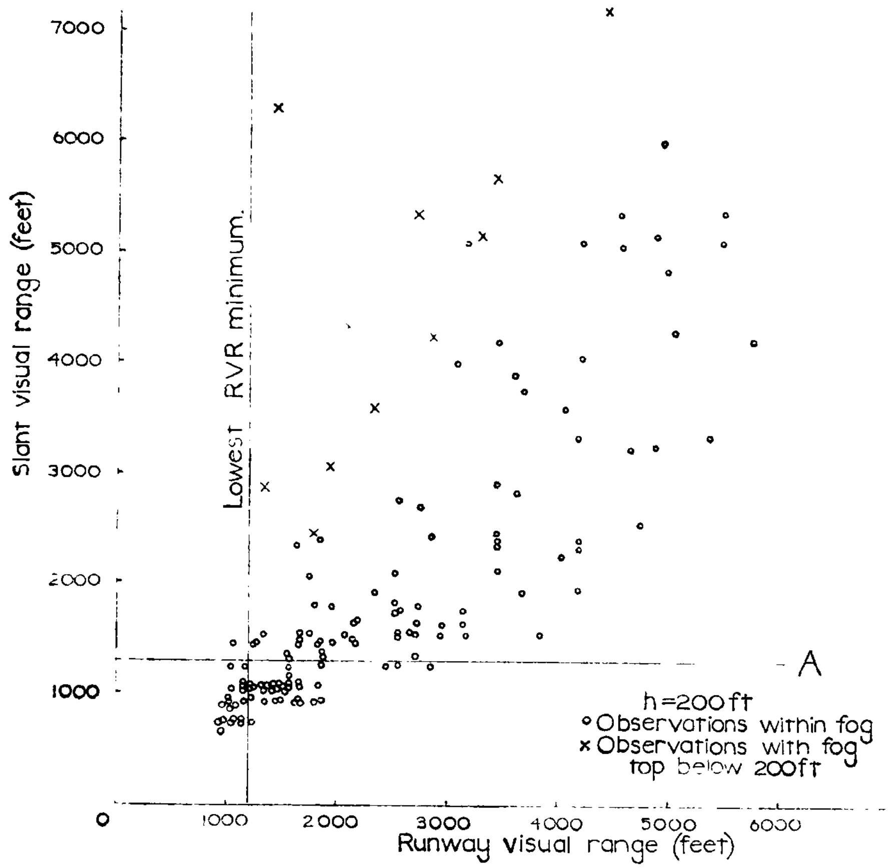

FIGURE 3 (*a*)

(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*).

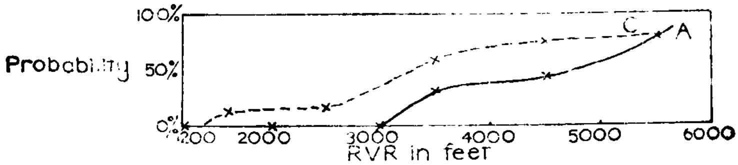

FIGURE 2(*b*)—PROBABILITY OF "ADEQUATE GUIDANCE" FROM 300 FT ON GLIDE SLOPE WHEN FOG TOP IS ABOVE 300 FT

———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*).

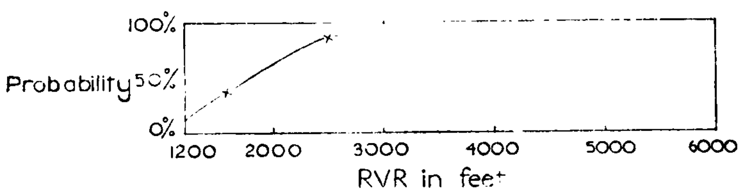

FIGURE 3(*b*)—PROBABILITY OF "ADEQUATE GUIDANCE" FROM 200 FT ON GLIDE SLOPE WHEN FOG TOP IS ABOVE 200 FT

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.

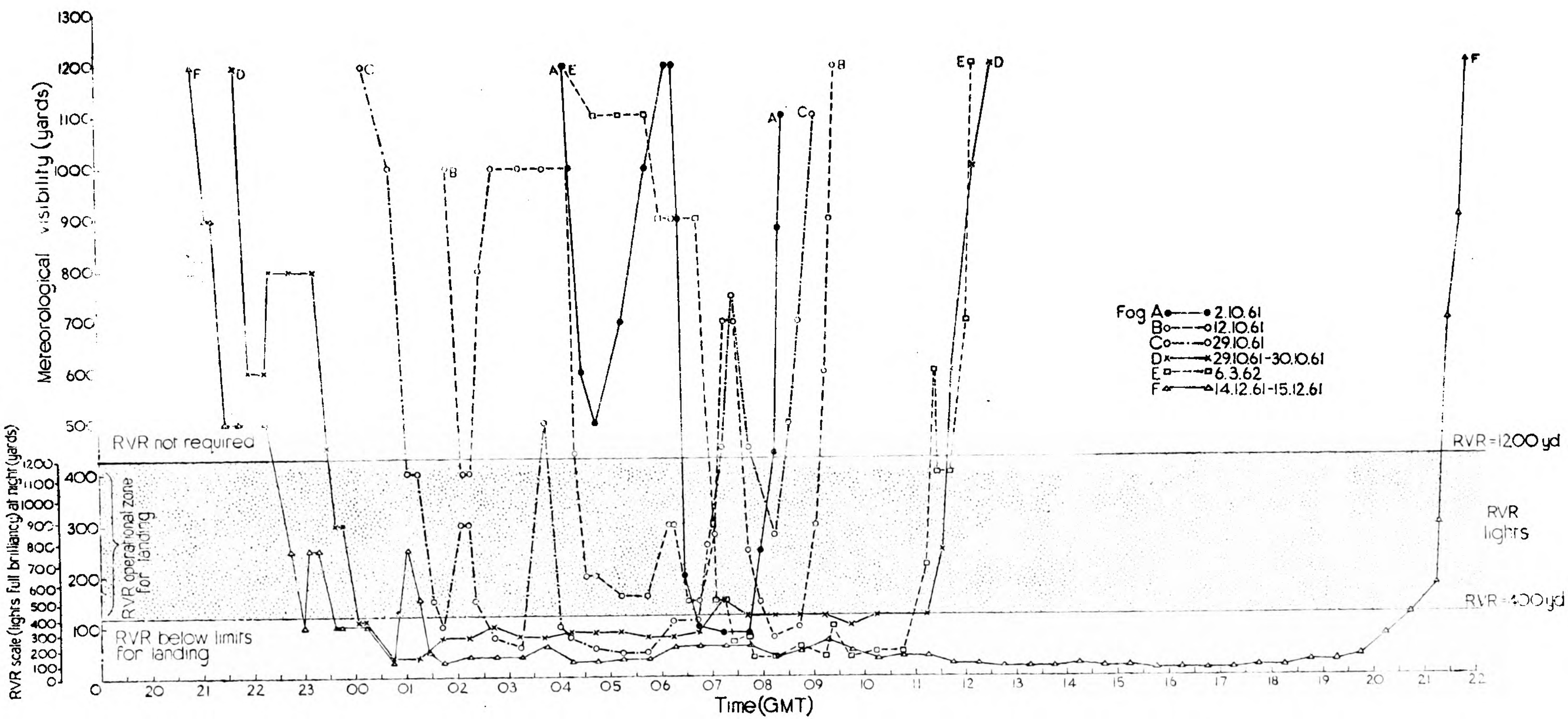

FIGURE 4 — RADIATION FOG AND RVR, LONDON (HEATHROW) AIRPORT

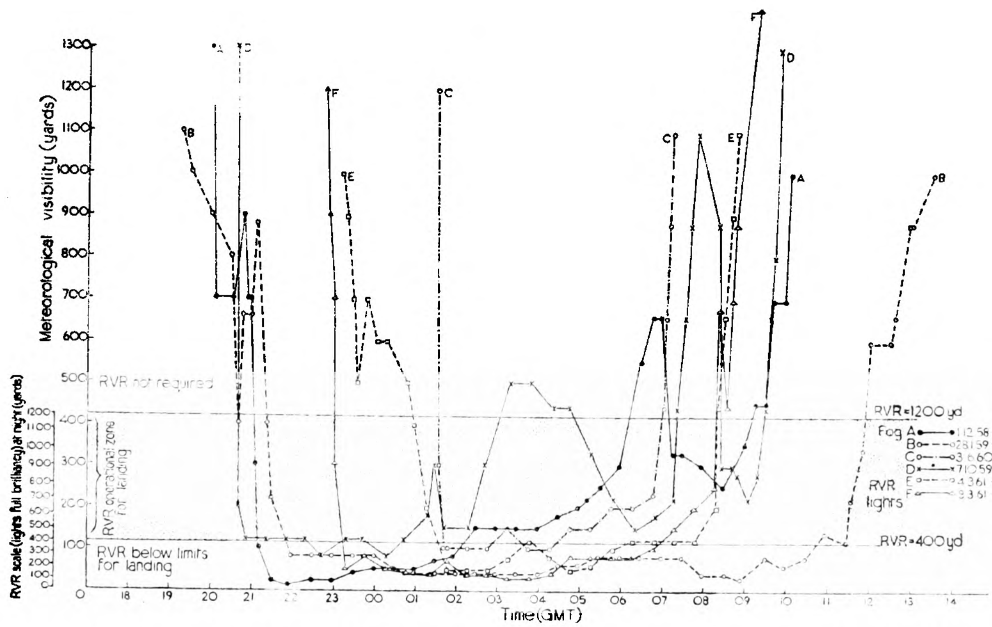

FIGURE 5 — RADIATION FOG AND RVR, LONDON (GATWICK) AIRPORT

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}.

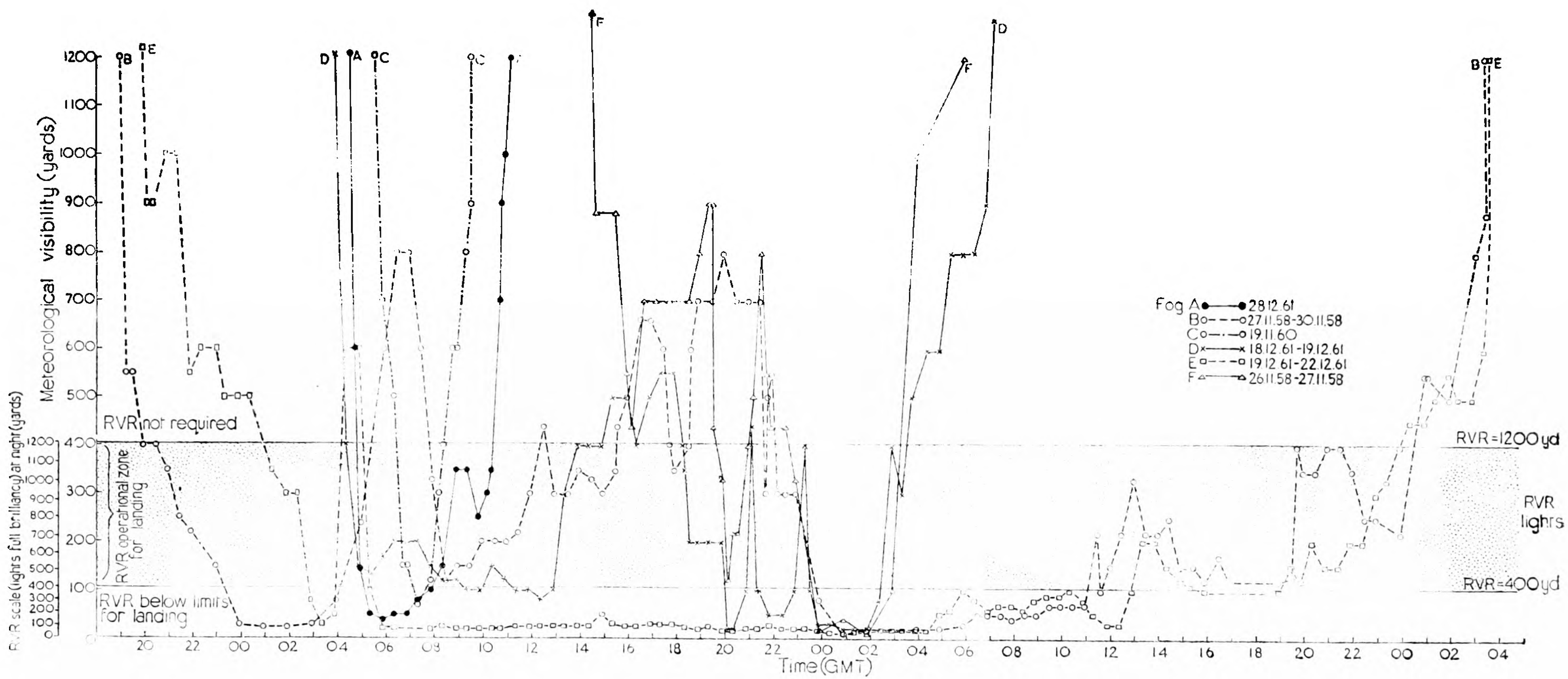

FIGURE 6 — RADIATION FOG AND RVR, MANCHESTER AIRPORT

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.

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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.

[To face p. 35

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.

METEOROLOGICAL OFFICE M.O. 738

THE METEOROLOGICAL MAGAZINE

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METEOROLOGICAL APPLICATIONS OF CONSTANT-VOLUME BALLOONS

By J. K. ANGELL
(U.S. Weather Bureau)

Introduction.—A previous survey article[1] has attempted to show the usefulness of the constant-level balloon both for operational meteorology and for meteorological research. This earlier article dealt mainly with constant-level balloon (transosonde) flights from Japan at heights of 30,000 and 35,000 feet, the flight at approximately constant level only being realized through the use of a complex and weighty ballast system. More recent constant-level balloon techniques involve the use of a superpressured, constant-volume balloon, thus eliminating the need for ballasting and greatly reducing the weight and cost of the balloon instrumentation. In this article we indicate some meteorological applications of constant-volume balloon flights at relatively low level.

Techniques.—A superpressured, constant-volume balloon maintains nearly constant-level flight without the release of ballast. The reason why this is so can be seen from the equation relating buoyancy force and weight of the balloon system

$$V_b \; (\rho_a - \rho_h) = W \qquad \ldots (1)$$

where V_b is balloon volume, W is system weight, and ρ_a and ρ_h are the densities of air and the inflating gas (hydrogen or helium), respectively. It is seen from equation (1) that if a balloon maintains constant volume it will tend to fly along a surface of constant density. Given a fully inflated non-extensible balloon, the balloon volume could only change owing to seepage of gas through the skin of the balloon or through decrease in temperature of the gas within the balloon either due to radiation or the lowering of the ambient air temperature. However, if initially the gas within the balloon has a considerably greater pressure than the air outside the balloon (superpressure), then in spite of the above processes the non-extensible balloon will maintain its full (and hence constant) volume and possess an equilibrium floating surface for some time.

Constant-volume balloon flights at relatively low level have been made with the so-called tetroons (*tetr*ahedron-shaped ball*oons*). These tetroons are made out of Mylar 1/500 of an inch in thickness, with the Mylar frequently aluminized to provide a radar reflective target. Mylar, being practically non-extensible and possessing high tensile strength and very low permeability, is a highly suitable material for constant-volume balloons and has only recently been developed (the ECHO satellite is made of Mylar). The tetrahedron shape allows the balloon seams to be straight lines, thus increasing the reliability and reducing the cost. Tetroons withstand a superpressure of 100 millibars with only a 1 per cent change in balloon volume.

Trajectories.—Probably the most obvious use for the constant-volume balloon is in the estimation of air trajectories or the trajectories of contaminants. As an example, Figure 1 shows three tetroon trajectories obtained at Yucca Flat, Nevada, within the proving grounds of the Atomic Energy Commission.

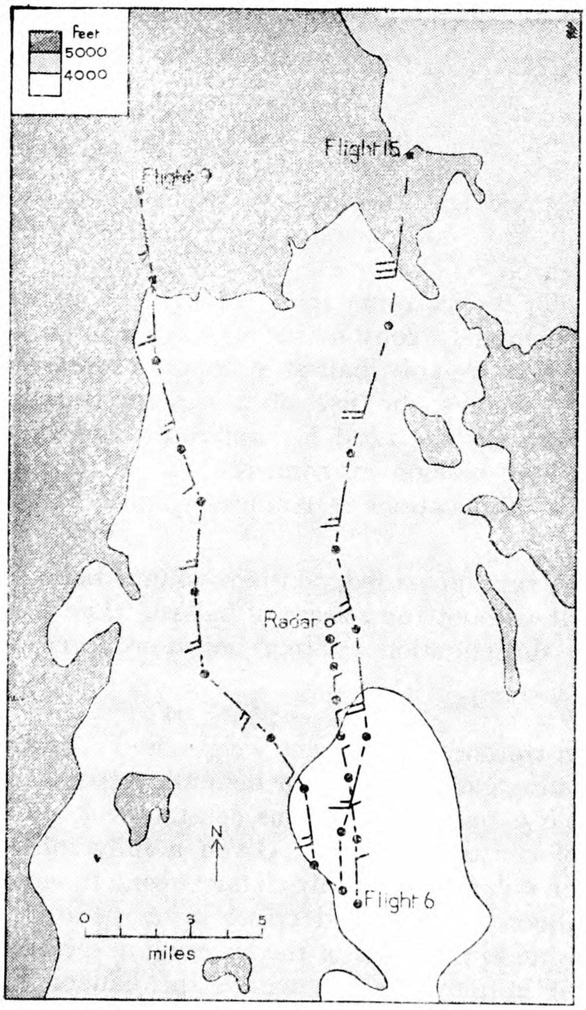

FIGURE 1—TRAJECTORIES OF THREE TETROON FLIGHTS AT YUCCA FLAT, NEVADA PROVING GROUNDS

Tetroon positions and winds at 10-minute intervals

Flight 6 was released at 2000, Flight 15 at 0900, and Flight 9 at 1200 local time, each on different days. As would be anticipated, the trajectories indicate the existance of a strong upslope motion during the day and a weak downslope motion during the night. Also, during the day the trajectories undergo rather large lateral oscillations whereas during the night the trajectories are quite straight. A series of such trajectories has shown a tendency for the air motion to veer with a pendulum day period during the daylight hours within Yucca Flat. The usefulness of such trajectories in delineating areas which would be affected by radio-active material is obvious.

Vertical oscillations.—It has been found that the tetroons are quite easily displaced from their equilibrium density surface. For example, Figure 2 shows the height change as a function of time for the three trajectories presented in Figure 1. The tetroon released in the middle of the day (Flight 9) undergoes height variations of thousands of feet whereas the tetroon released during the

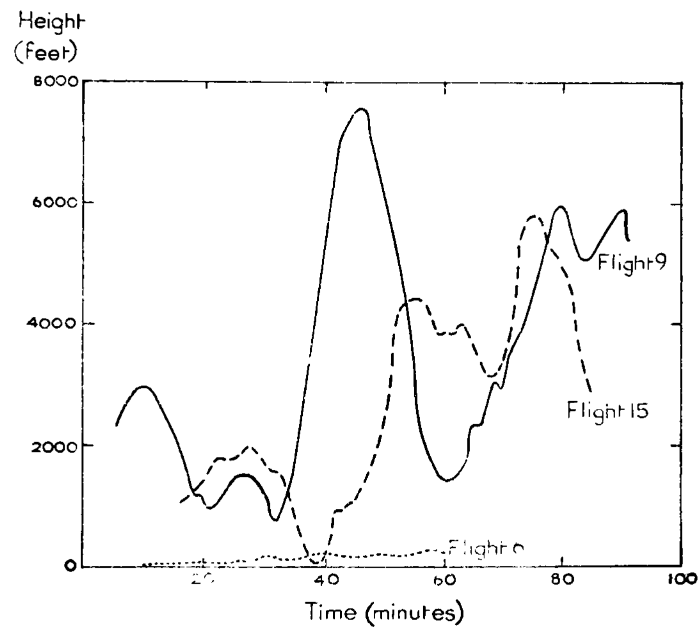

FIGURE 2—TETROON HEIGHT AS A FUNCTION OF TIME FOR THE THREE FLIGHTS OF FIGURE 1

Flight 9 released at 1200, Flight 15 at 0900, Flight 6 at 2000 local time.

evening (Flight 6) undergoes height variations of tens of feet. Data such as these suggest that the tetroon trajectory represents at least a first approximation to the three-dimensional air parcel trajectory. Owing to the tendency for the tetroon to return to its equilibrium surface, however, the tetroon oscillations in the vertical would be expected to be of smaller amplitude than the air parcel oscillations in the vertical. As a matter of interest, during midday flights in Yucca Flat, the vertical tetroon velocity occasionally exceeded the horizontal velocity.

In order further to examine the relationship between tetroon trajectory and air parcel trajectory, the predominant period of tetroon oscillation in the vertical was compared with the period theoretically to be expected for air parcels,[2] that is

$$\tau = 2\pi \left[\frac{T_0}{g\,(\gamma_p - \gamma)}\right]^{\frac{1}{2}}, \qquad \ldots (2)$$

where τ is the period of vertical oscillation, T_0 is the ambient air temperature, g is the acceleration due to gravity, γ_p is the process lapse rate (usually assumed dry adiabatic), and γ is the lapse rate. In Figure 3 this predominant period of tetroon oscillation in the vertical (as determined from spectral analysis) has been plotted as a function of lapse rate. The unstarred numbers represent tetroon flights from Yucca Flat in Nevada, the starred numbers

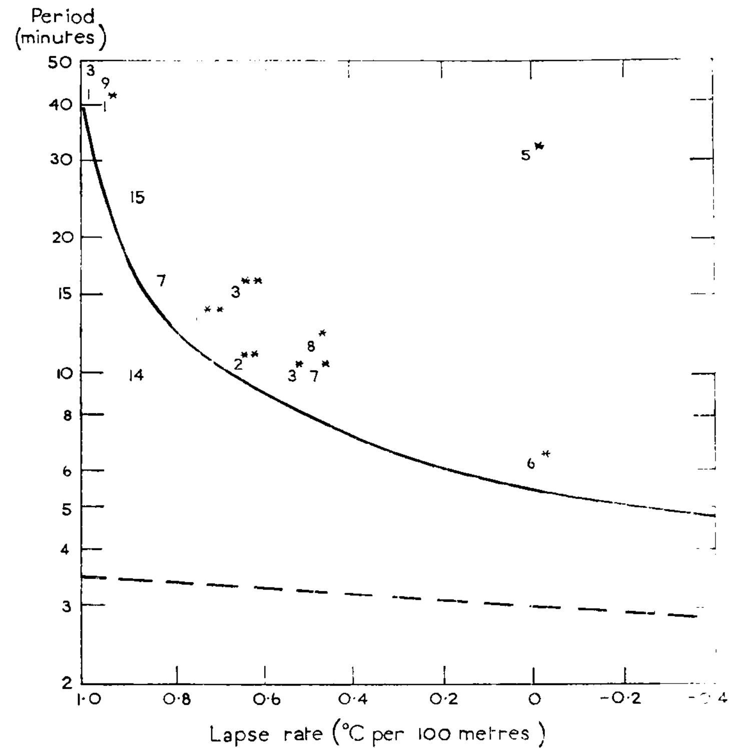

FIGURE 3—THEORETICAL PERIOD OF VERTICAL OSCILLATION OF AIR PARCELS (SOLID LINE) AND CONSTANT-VOLUME BALLOONS (DASHED LINE) AS A FUNCTION OF LAPSE RATE

The plotted numbers show the predominant period of vertical oscillation (spectral peak) along individual tetroon flights.

flights from Wallops Island over the Atlantic Ocean, and the double-starred numbers flights from Easthampstead and Cardington in England. On the two longest tetroon flights (Flights 1* and 3*) it is believed refractive effects at extreme distances have introduced fictitious high-frequency oscillations in the vertical, and consequently for these flights the periods corresponding to secondary lower-frequency spectral peaks have been entered in the figure. It would appear from Figure 3 that the predominant period of tetroon oscillation in the vertical is much nearer to that derived theoretically for an air parcel (solid line) than for a constant-volume balloon (dashed line). Thus this figure, as well as presenting evidence that vertical oscillations with a basis in theory do occur in the atmosphere, suggests that the tetroons tend to follow the vertical air motions rather than undergoing vertical oscillations associated with their own buoyancy.

Two anomalies in Figure 3 are Flights 5* and 14. Flight 5* is of interest in that it was released during the passage of a weak cold front over Wallops Island.

Flight 6* was released 20 minutes later but was tracked by a somewhat inferior radar. However, the positioning of Flight 6* was sufficiently accurate to show that the tetroon underwent vertical oscillations similar to those found along Flight 5* but displaced about two miles downstream. Data derived from these two flights permitted estimation of the speed and direction of travel of the vertical motion pattern traversed by the two flights[3] (about five knots in the general direction of the tetroon trajectories), and hence allowed for the determination of the streamline pattern along both flights as shown in Figure 4.

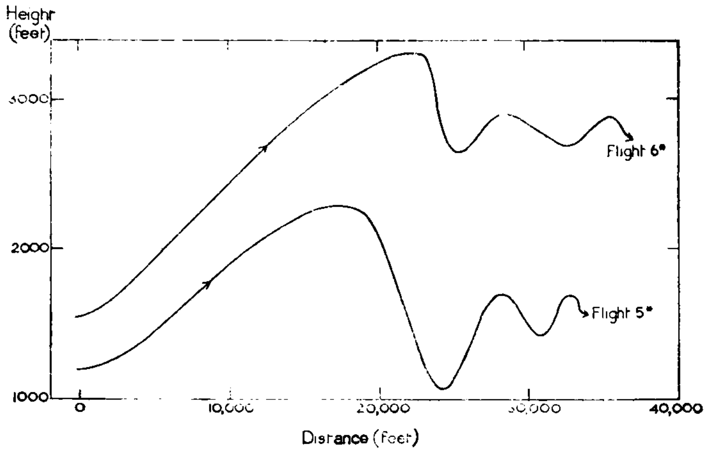

FIGURE 4—SMOOTHED STREAMLINES DERIVED FROM THE TRAJECTORIES OF OVER-WATER TETROON FLIGHTS 5* AND 6*

Note that the vertical scale is exaggerated 10 times with respect to the horizontal scale.

The difference in streamline structure indicated in Figure 4 could be due to the small difference in time of the flights or to their difference in altitude. These vertical motion patterns were moving nearly at right-angles to the frontal intersection with the ground and approximately in the direction of the vertical wind shear through the front. Thus they may well be associated with undulations in the frontal surface occasioned by vertical wind shear. If this is so, then it is not surprising that the predominant periodicity of vertical oscillations along Flight 5* is not solely a function of stability, as apparently is the case with many of the flights plotted in Figure 3.

Tetroons appear as logical instruments to investigate mountain-induced vertical air motions, especially when one considers the interesting results obtained by Gerbier and Berenger[4] using zero-lift balloons. Originally it was hoped that tetroon flights from Yucca Flat could serve as the basis for such an investigation. However, the vertical oscillations during the day due to solar heating were so large (Figure 2) that they masked any vertical oscillations due to topography, while the tetroon flights during evening and early morning were usually confined to Yucca Flat itself. Only Flight 14, which was towed aloft by a radiosonde balloon, fulfilled the criterion of a flight traversing mountainous terrain during a time of negligible solar heating. This flight passed over mountain ridges spaced at approximately four-mile intervals. Figure 5 shows the vertical oscillations of the tetroon with respect to a schematic mountain ridge similar in dimension to the actual mountain ridges. The dotted

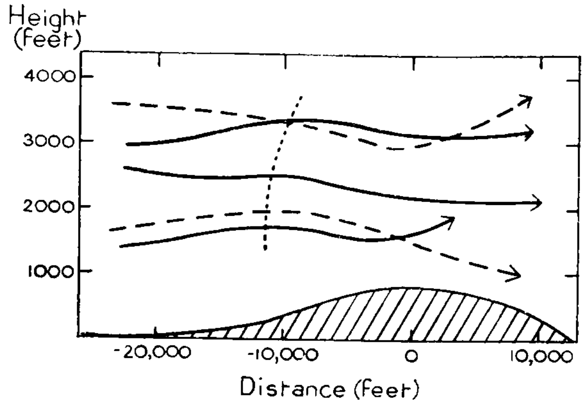

FIGURE 5—SEGMENTS OF THE TRAJECTORY OF TETROON FLIGHT 14 (SOLID LINES) IN RELATION TO (SCHEMATIC) MOUNTAIN RIDGES

The dashed lines are streamlines deduced theoretically by Queney for a medium-sized mountain. Dotted line is locus of maximum tetroon heights.

line connecting points of maximum tetroon height shows that this height was attained almost two miles upstream from the mountain crests and hence the tetroon oscillations were nearly out of phase with the variations in ground height. The trajectories agree only vaguely with the streamlines (dashed lines) deduced theoretically for a medium-sized mountain by Queney.[5] Nevertheless, it is not unreasonable to state that the mountain ridges were inducing tetroon oscillations in the vertical, and with a tetroon velocity of 24 knots and the given ridge spacing, this would yield the vertical oscillations of about ten-minute period found along this flight (Figure 3). A periodicity of nine to ten minutes in the lateral velocity component along Flight 14 suggests that this component was also influenced by the mountains.

Helical circulations.—Most of the day-time tetroon flights over Yucca Flat gave evidence for the existence of helical circulations, although in many cases the flights were too short for a really satisfactory demonstration. Figure 6(*a*) illustrates this helical tendency along Flight 9 (see also Figures 1 and 2).

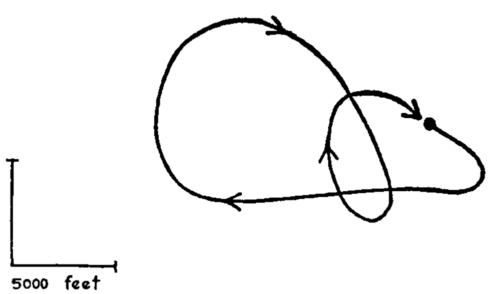

FIGURE 6(*a*)—CIRCULATIONS IN THE TRANSVERSE PLANE ALONG FLIGHT 9

The sense of the helical circulation appeared random when all the day-time flights over Yucca Flat were considered.[6] Of the flights over the sea, however, only Flight 3* exhibited a consistent helical circulation pattern as shown in the somewhat smoothed diagram, Figure 6(*b*). The six circulations in the transverse plane on this 60-minute flight yield a 10-minute periodicity as shown in Figure 3. Note that the helical circulations along Flight 3* are of an order of magnitude smaller than those along Flight 9 and perhaps could only have

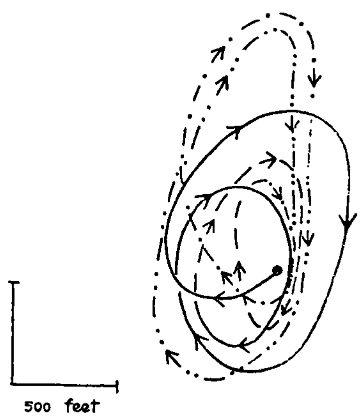

FIGURE 6(*b*)—CIRCULATIONS IN THE TRANSVERSE PLANE ALONG FLIGHT 3*
Note that the scales on Figures 6(*a*) and 6(*b*) differ by an order of magnitude.

been detected through the use of the excellent FPS–16 tracking radar based at Wallops Island. There is no doubt that great care must be exercised in relating these helical tetroon motions to helical air parcel motions since there is always the tendency for the tetroon to return to its equilibrium floating surface. In the case of Flight 9 the large vertical air motions would probably mask any such tendency but this may not be true in the case of Flight 3*. In any event, it is not obvious why helical tetroon circulations existed along over-water Flight 3* when they did not exist under similar stability conditions along over-water Flights 7* and 8*. Insofar as a fairly high wind speed at 3000 feet implies a fairly large wind shear in the vertical, these results could be placed in agreement with model experiments which show that as the vertical shear is increased, the circulation changes from vertical convection (Bénard Cells) to transverse rolls, to longitudinal rolls (helices), to chaotic vertical motion.[7] However, of late there has been some doubt as to the applicability of these model experiments to atmospheric conditions, despite the similarity in results obtained by Woodcock[8] through observations of the soaring of seagulls.

Dispersion estimates.—Dispersion estimates are most naturally made utilizing Lagrangian data, that is, data derived from the trajectories of individual air parcels. Inasmuch as there is evidence that tetroon trajectories approximate to air parcel trajectories, it is reasonable to estimate dispersion directly from tetroon data. It has been shown by Pasquill[9] that after travel time T the crosswind particle variance $Y^2(T)$ is given by

$$\overline{Y^2(T)} = \overline{(V'_T)}\, T^2, \qquad \ldots (3)$$

where $\overline{(V'_T)^2}$ is the crosswind variance of the Lagrangian velocity averaged over T. This equation expresses the intuitively obvious fact that, for short travel times, oscillations of all frequencies contribute to the dispersion whereas for long travel times the low frequency oscillations dominate the dispersion. If Lagrangian data are available, equation (3) appears an extremely easy way of estimating dispersion. There are, however, subtle difficulties involved in the use of even so simple an equation, partly due to the assumptions on which the equation is based and partly to limitations in the data now available to substitute in the equation. These difficulties have been treated elsewhere[10] and it must suffice here to state that the most serious limitation involves the fact that the dispersion should probably not be estimated for travel times exceeding one-tenth the duration of the tetroon flights.

Figure 7 shows the standard deviation of particle displacement in the crosswind direction at downwind distances of 0.5, 1.0 and 2.0 nautical miles as derived from Yucca Flat tetroon flights at varying times of day. These standard deviations were obtained by applying equation (3) to crosswind velocity components derived from radar positionings at one-minute intervals. Worthy of note are the apparent influence of the ground on the dispersion estimated from the lower of the two 0600 flights and the evidence that in the morning,

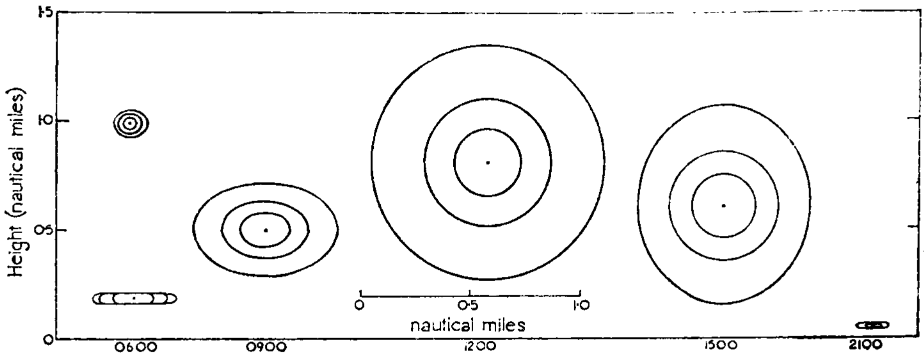

FIGURE 7—STANDARD DEVIATIONS OF VERTICAL AND LATERAL PARTICLE DISPLACEMENT AT DOWNWIND DISTANCES OF 0.5, 1.0 AND 2.0 NAUTICAL MILES (ELLIPSES) AS DERIVED FROM YUCCA FLAT TETROON FLIGHTS AT VARIOUS HEIGHTS AND TIMES OF DAY

when the vertical instability is on the increase, the lateral dispersion is greater than the vertical dispersion, whereas at noon the dispersion in the two directions is equal and in the afternoon the vertical dispersion exceeds the lateral dispersion. Based upon these data, one would estimate the axial concentration of an effluent released at 2100 local time at Yucca Flat to be two to three orders of magnitude greater than the concentration of an effluent released at noon. Thus, in addition to giving the trajectory of an effluent, even a single tetroon trajectory can yield an estimate of the effluent concentration.

In addition to the dispersion from a continuous point source, considerable interest also attaches to relative dispersion or the growth of an individual cluster of particles. Basically, this "smoke-puff" type of dispersion depends upon the increase in distance between pairs of particles and thus is more complex than the continuous point source in that it involves, at the minimum, the obtaining of two trajectories at the same time. Tetroons are just beginning to be used to estimate this type of dispersion but previous attempts along this line have included the use of vertically ascending pilot balloons[11] and zero-lift pilot balloons.[12] The advantage of tetroons over expansible balloons in this type of analysis resides in the fact that the tetroons should better maintain flight altitude and hence the vertical wind shear should not play so great a role in the observed dispersion.

As a preliminary example of the relative dispersion results obtainable from tetroons, Figure 8 shows, as a function of time, the square of the distance separating two simultaneously released tetroons at Cincinnati, Ohio. This trace has been highly smoothed; in fact, the unsmoothed data indicate that at times the tetroons actually moved closer to each other. The smoothed data in

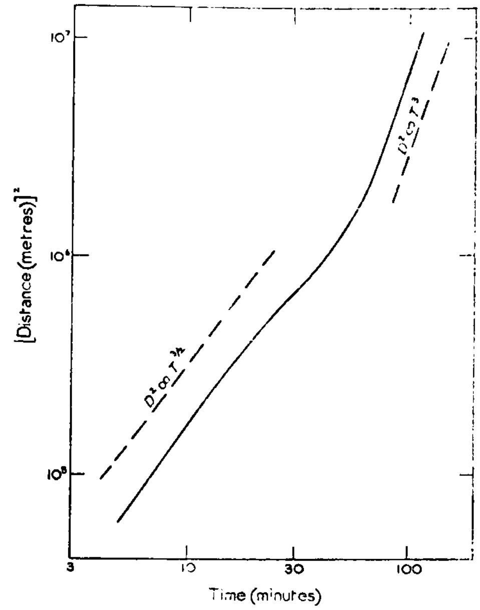

FIGURE 8—SQUARE OF THE DISTANCE BETWEEN TWO SIMULTANEOUSLY RELEASED TETROONS AS A FUNCTION OF TIME

The dashed lines show the power of the time to which the square of the distance is proportional.

Figure 8 show that initially the square of the distance increased approximately as the 3/2 power of the time whereas toward the end of the tracking the increase was near the third power of the time. Overall, the tetroons separated from each other at an average speed of about one knot. Of course, it is impossible to generalize from one experiment, but the results shown in Figure 8 are in general agreement with relative dispersion data on a much smaller scale.[13]

Eulerian–Lagrangian comparisons.—It has been shown above that it is possible to estimate atmospheric dispersion by forming the product of the square of the travel time and the variance of the Lagrangian velocity averaged over the travel time. However, inasmuch as Eulerian (fixed point) statistics are much more easily obtained than Lagrangian (air particle attached) statistics, it is desirable to investigate the possibility of a relationship between these two sets of statistics. Following the fundamental paper of Hay and Pasquill,[14] Eulerian–Lagrangian comparisons near ground level have been made by many people, mainly using the dispersion of fluorescent dye to yield an indirect estimate of the Lagrangian statistic. It has been deduced from these experiments that the period of oscillation in the Lagrangian system exeeds that in the Eulerian system by a factor of about four ($\beta = 4$). At elevations considerably above the ground Eulerian–Lagrangian comparisons are obtained with difficulty. Several years ago Gifford[15] showed the possibility of using zero-lift pilot balloons to estimate the Lagrangian statistics. This method has the disadvantages that the volume (and hence buoyancy force) of the pilot balloon changes in response to heating and cooling and that the pilot balloon has to be released at its equilibrium floating level, making very difficult flights more than a few hundred feet above the ground. The constant volume tetroon with its capability for flight at any height with a ground release appears a more appropriate tool to investigate Eulerian–Lagrangian relationships.

Panofsky and McCormick[16] have shown that if the product of frequency and vertical velocity variance per unit frequency interval is plotted as a function of nz/V (n is frequency, z height above ground, V wind speed), the near-ground Eulerian spectra culled from various sources all exhibit a peak at a value of nz/V between 0.1 and 1.0. They also reproduce a diagram taken from a paper by Lappe, Davidson and Notess[17] showing the mean position of the Eulerian spectral peak of vertical velocity at Brookhaven up to heights of 1600 feet. More recently, F. B. Smith[18] has presented a table giving positions of Eulerian spectral peaks of vertical velocity at Cardington at heights up to 2000 feet. As background material, it is of interest to make comparisons between these data and tetroon data even though the latter were obtained at other places and at other times.

The non-underlined flight numbers in Figure 9 show the predominant periodicity of vertical motion (spectral peak) along individual tetroon flights at functions of flight altitude and nz/V. The solid curve labelled C has been obtained by averaging Smith's Cardington results at heights of 500, 1000, and

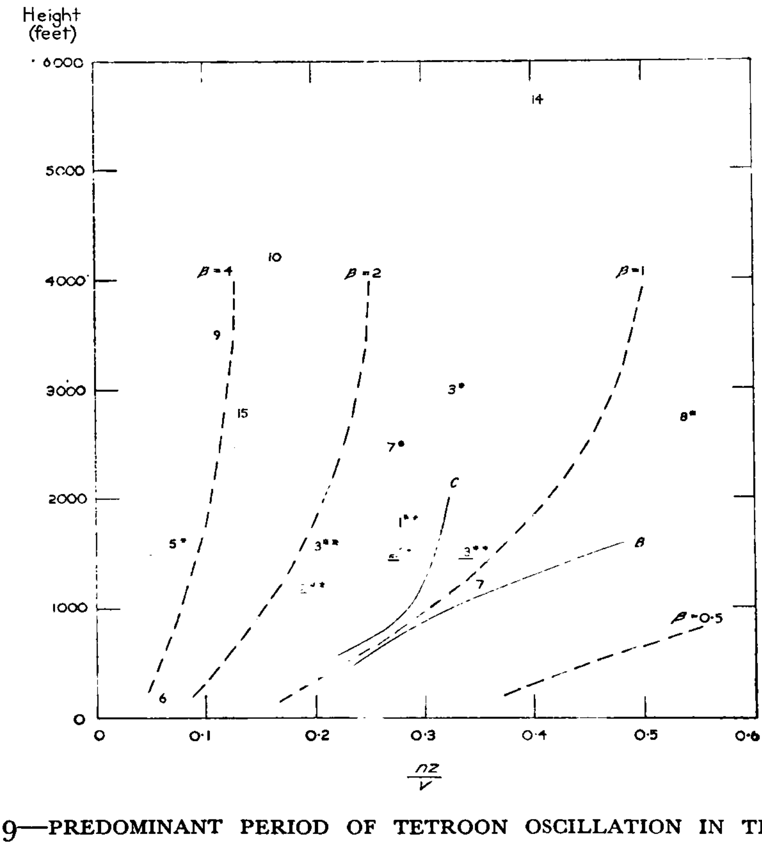

FIGURE 9—PREDOMINANT PERIOD OF TETROON OSCILLATION IN THE VERTICAL (NON-UNDERLINED FLIGHT NUMBERS) AS A FUNCTION OF TETROON HEIGHT AND nz/V, AND MEAN POSITION OF EULERIAN SPECTRAL PEAKS AT CARDINGTON (SOLID LINE C) AND BROOKHAVEN (SOLID LINE B)

Underlined numbers show position of Eulerian spectral peaks at time of tetroon flights.

2000 feet, while the solid curve labelled B is taken from the aforementioned Brookhaven data. As deduced from an interpolation between, and extrapolation of, the Cardington and Brookhaven results, the dashed lines show the values of β for various plottings of tetroon flight numbers. There is, of course, a great danger in comparing Eulerian and Lagrangian data in this way inasmuch as the two kinds of data were obtained in different places at different times.

As an example, from the vertical oscillations along Flights 5* and 6* it has been determined that the tetroons are moving through the vertical motion pattern at the same speed the vertical motion pattern is moving over the ground so that in this case $\beta = 1$. However, in Figure 9, Flight 5* is positioned near the line $\beta = 4$. With these dangers clearly in mind, note from Figure 9 that only Flight 8* falls obviously in the $\beta < 1$ region whereas day-time flights over the desert fall near $\beta = 4$ and flights over the sea generally fall near $\beta = 2$.

At Cardington an attempt is being made to relate Eulerian–Lagrangian statistics by flying tetroons past an instrumented barrage-balloon cable. Only two such direct comparisons are available for presentation here. The underlined numbers 2** and 3** in Figure 9 show the positions of the Eulerian spectral peaks of vertical velocity for the times tetroon Flights 2** and 3** were aloft. The positions of these Eulerian spectral peaks agree well with the mean positions determined from Smith's data. From the relative positions of the Eulerian and Lagrangian spectral peaks one would estimate that during Flight 2** $\beta = 1.5$ and during Flight 3** $\beta = 1.7$. The respective turbulence intensities in the vertical were 0.20 and 0.10. It must be admitted, however, that the Lagrangian spectral peaks were ill-defined on these two flights and consequently these preliminary results should not be taken too literally.

Conclusion.—The evidence that a constant-volume balloon trajectory represents an approximation to a three-dimensional air parcel trajectory suggests the use of tetroons in many fields of investigation other than those mentioned herein. Future studies will include tetroon flights in the Los Angeles Basin for the purpose of delineating trajectories of pollutants and flights within severe storm areas for the purpose of better determining the vertical air motions. Tetroons would also appear logical instruments with which to investigate mountain waves but as yet no specific programme is in mind. There is every reason to believe that the value of the constant-volume balloon will become more and more obvious as time goes on.

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FUMULUS

By E. N. LAWRENCE, B.Sc.

The term 'fumulus' has a long history in meteorological literature but, though there has been a revival in its use during the last decade or so, it has no generally accepted definition. The following notes show that over the course of nearly a century, the word which originally described a nascent form of cumulus became associated, probably due to literal or incorrect translation, with smoke and fumes, until, regarded as a popular pseudo-scientific term, it is no longer included in the international classification of cloud forms.

The Annals of the Meteorological Society of France of 1880, contain a paper by Ritter[1] in which he states, with reference to the early stages of cumulus growth, that the 'cloud' first becomes visible as constantly changing and sometimes transient whirls, resembling the capricious movement of light smoke (fumée) and aptly described by the word 'fumulus'. This description of 'fumulus' suggests a fuller understanding of the processes peculiar to the development of fractocumulus than the earlier reference to fractocumulus as "wind-cloud".[2, 3]

For many years, publications mentioned 'fumulus' with reference to Ritter and associated it with fractocumulus. For example, in 1917 a Rome[4] publication so refers to a 'species' — 'fumulus', and the *International Atlas of Clouds* (1932[5] and 1939[6], though not the very brief first edition of 1896[7] or the recent 1956[8] edition) and the *Handbook of Meteorology*[9] give the following description:

"**Fumulus** (*Fum.*)–*Ritter* 1880. At all levels, from Cirrus to Stratus, a very thin veil may form, so delicate that it may be almost invisible. These veils seem to be most frequent on hot days, and in low latitudes. Occasionally they may be observed to thicken rapidly, forming clouds easily visible, especially Cirrus and Cumulus. The clouds thus produced seem unstable, however, and usually melt away soon after their formation.

"Cirrus fumulus must not be confused with Cirrostratus nebulosus. The latter is more stable and does not show the phenomenon of the formation and subsequent rapid disappearance of Cirrus clouds."

[Cirro-nebula is a variety which was first suggested by the Rev. W. Clement Ley[10]: cirrostratus nebulosus is referred to by Abercromby[10] and Clayden[11], and is defined in the *Handbook of Meteorology*[9] as "a very uniform light nebulous veil, sometimes extremely thin, hardly visible and sometimes relatively dense but always without definite details and with halo phenomena".]

The *International Atlas of Clouds*[5, 6] includes, in addition, a plate depicting "Clouds associated with moderate convection" and, in particular, a form of "cloud" in which "condensation is only beginning" and which is "hardly visible"; this "cloud" is referred to as the "fumulus stage" of the (moderately) convective cloud.

In approximate conformity with the main text of the *International Atlas of Clouds*,[5, 6] Perrie[12] refers to fumulus as follows:

"The first cloud produced by thermal updrafts usually takes the form of fractocumulus. Fractocumulus is a ragged cloud, and takes very irregular forms, ... Veils of mist observed to precede the actual formation of these clouds are sometimes known as *fumulus*."

From about 1950, the term 'fumulus' rapidly became very popular in meteorological literature, but was used more diversely. For instance, the term was applied to cloud originating from plumes from chimneys, and Scorer[13] refers to an "unwashed plume rising to cloud base and forming 'fumulus' bubbles". His diagram shows outlines of visible matter partly above and partly below lines representing the general cloud (condensation) levels. This definition implies that 'fumulus' is primarily water cloud of cumuliform type and, in this instance, above a mass of smoke in which there is either practically nil or limited condensation (that is, water content less than in ordinary cumulus). A comparable definition is suggested by a photograph[14] published with the caption, "Fumulus: small cumulus clouds formed by a heath fire near Bordon, Hampshire, 17 March". The burning source would itself contribute to the total atmospheric moisture[15] and help to lower the condensation level.

This lowering of condensation level by the addition of moisture is illustrated by observations of ship-made cloud formed with the aid of funnel exhaust:[16] artificial cloud appeared to form either below that of the natural cloud formation[17] or lower than that suggested by surface dry-bulb and dew-point temperatures.[18, 19] The assistance of artificial heat to natural convection is suggested by two such observations: one [20] refers to cloud forming only in the vicinity of existing tufts and the other[18, 21] to the formation of ship cumulus where and when the sea appeared chocolate-coloured and extremely opaque, due to marine organisms. Artificial (water) cloud may form more easily over sea than over land on account of the greater marine tendency for neutral stability with adequate moisture: also, similarity between the speed and direction of movement of ship and atmosphere would help to maintain such cloud (there being little or no wind shear relative to the moving heat source). One ship report[18] refers to the gradual transition from smoke to cumulus: it states that "the exhaust gases rising slowly from the funnel were seen to change gradually from blue-grey to white" (fumulus?) "and after some minutes a small puff of what seemed to be fair weather cumulus formed over the vessel at an estimated height of 100–200 ft. over the sea. Air temp. 70.4° F, dew point 64°. Wind S'W, force 4–5. Ship's course 010° at 16.3 kt."

The current *International Cloud Atlas*[8] contains a section on clouds from fires (describing for example convective, mainly water-droplet cloud from a certain level upwards, bulging up out of smoke cloud) and a plate depicting 'smoke layer cloud' but, however, no reference to fumulus. It is stated therein that "In spite of the similarity of form between such fire clouds and cloud produced by ordinary convection (Cumulus congestus and Cumulonimbus), the former can easily be recognized by the rapidity of their development and by their dark colour". While this may be true of the towering mushroom cloud from an atomic explosion or volcanic eruption, the intensity and direction of illumination and the type of background have considerable effects on cloud appearance (see for example Scorer[22]) and identification is often inferred from the surrounding topography.

Plate I (facing p. 52) shows a mass of cloud centred over the industrial town of Halifax (about 400 feet above mean sea level), looking north-west from a point about 700 feet above mean sea level, at 0930 GMT, 22 December 1957: the weather was generally cloudy, with cirrus and altocumulus and poor visibility; according to the *Daily Weather Report*, Halifax was in a warm sector. Plate II (facing p. 52) shows a similar view at 0935 GMT, 23 August 1958, when visibility was good. The height of the low cloud top was estimated from the photographs to be roughly 1000 feet above ground level. The low cloud was rather dark against the light upper cloud but, on the whole, synoptic and local conditions suggest predominanlty water cloud. The underside of the cloud appears to merge with smoke from the many local sources of pollution (see Plate I) feeding the 'fumulus' (?) from below. The base of the cloud may be associated with the level of maximum concentration of pollution: a local study[23] suggests that there is a level of maximum mean sulphur dioxide concentration at about 900 feet above mean sea level, that is, about 500 feet above central Halifax. Convergence due to artificial heating[24] below the cloud may be reinforced by local convergence due to orography and/or nocturnal cooling of surrounding hills. The latter factors may well have helped to increase stability at the level of the flat cloud top.

A recent book[25] refers to 'fumulus' as a yellow or brown smoke layer cloud (sometimes called high fog), and ascribes this definition to Scorer who, however, repudiates the statement[26] and says that 'fumulus' is essentially cumuliform. Later, a publication[27] of the Meteorological Office compromises with the following description:

"When the unsaturated bubbles can hardly reach the condensation level, their presence in a smoky atmosphere may be shown by the beginnings of condensation, giving misty patches in the same way that mist forms before a smoke fog even though the air is not saturated. These 'fumulus' clouds may grow into normal *Cu.*"

This is consistent with a recommendation made by Scorer in 1962 to use the term 'fumulus' for the dome-shaped masses produced by 'pollution thermals' before the general condensation level (100 per cent humidity) is reached. According to some of the later descriptions, this type of cloud might have been referred to as the 'sub-fumulus': it could, for example, be formed as a result of diurnal heating and turbulence breaking up a thick, polluted, stable layer. When practically no water is present, the resulting globules of dense pollution could be aptly described by the word 'smogulus'; one can thus reserve the word 'fumulus' for clouds with limited water content which precede the final indistinguishable 'water' (or normal) cumulus.

These three categories are clearly illustrated in a photograph[28] of 'a cloud formed on the top of a smoke plume produced by a grass fire' and which is reproduced as Plate III; dark billowing smoke (smogulus?) is merging up into a cloud with bulging light patches of condensation (fumulus?), which in turn merges into a white mass of normal cumulus above. The latter two types occur, in this instance, where the plume spreads out horizontally and probably thereby experiences greater cooling by mixing.

The word 'fumulus' should have a standard definition or be replaced by any suitable ramifications, such as 'cumulofumus' and/or 'cumulosmogus', for useful re-inclusion in the *International Cloud Atlas.*

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ANALYSIS OF A WEAK DISCONTINUITY AT MALTA, 2 SEPTEMBER 1960

By T. H. KIRK

The problems of analysis and forecasting in the Mediterranean area have received much attention recently. Few examples are available, however, to demonstrate the nature of the difficulties. The occurrence of a weak "discontinuity" at Malta on 2 September 1960 has been selected for illustration, firstly because it demonstrates the necessity for attention to detail and secondly, because it provides some evidence of the significance of the "pressure jump" to which reference has already been made in a previous note.[1]

The day at Malta had been fine with very light winds, mainly between south and east. At about 2000 local time (1900 GMT) the wind became completely calm but between 2300 local time and midnight it shifted to north-west, remaining very light and intermittent (see Figure 1). Cloud during the day

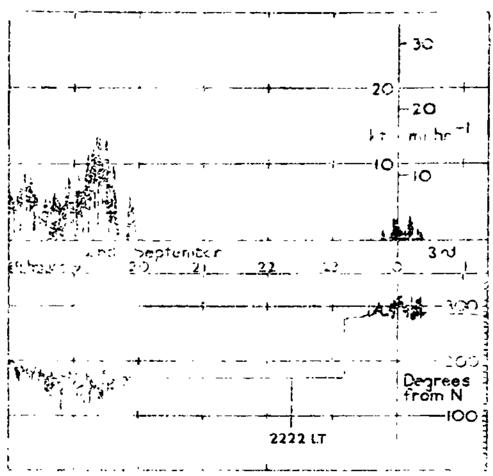


FIGURE 1—SURFACE WIND AT LUQA, 2 SEPTEMBER 1960

had been one to three oktas of unstable altocumulus until 2315 GMT when the occurrence of three oktas of low stratus at 800 ft necessitated the issue of a special report. Patches of stratus persisted throughout the night until 0745 GMT the following day.

Figure 2 shows the barograph trace during the evening. Making the necessary corrections from the time marks it is seen that the main pressure rise was initiated at approximately 1940 local time by a pressure jump which, although small, is nevertheless unmistakable. Its arrival coincided with the sharp fall in wind speed between 1900 and 2000 local time shown on the anemogram. The minor kink in the barograph trace at approximately 2300 local time corresponds with the veering of the wind to north-west. The thermogram (Figure 3) shows a discontinuity of temperature gradient at about 2045 local time followed by a less marked discontinuity at about 2300 local time corresponding with the onset of the north-westerly wind.

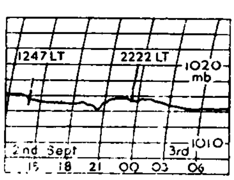


FIGURE 2—BAROGRAM FOR LUQA, 2 SEPTEMBER 1960

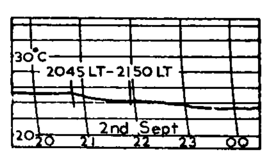
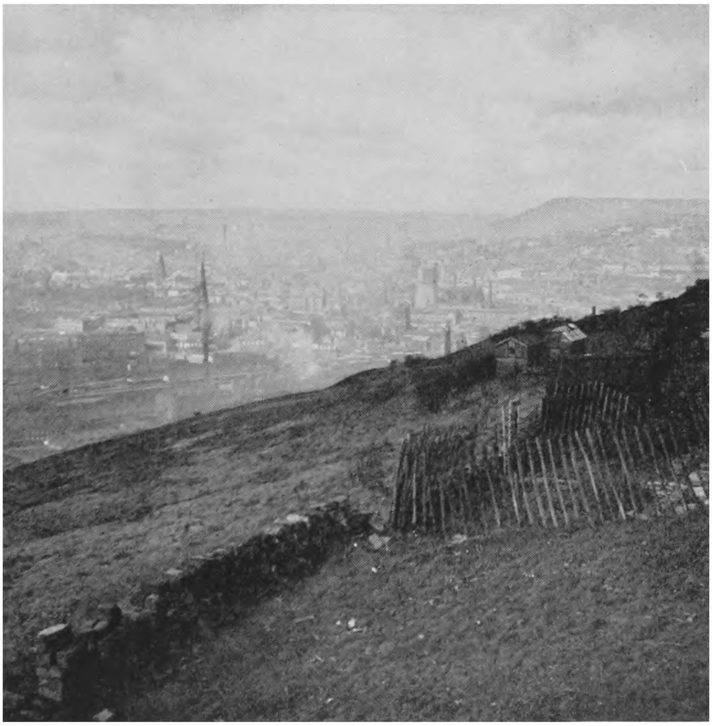


FIGURE 3—THERMOGRAM FOR LUQA, 2 SEPTEMBER 1960

Turning now to the synoptic situation, Figures 4, 5, 6 and 7 show the sequence of events at the surface at 0600, 1200 and 1800 GMT, 2 September and 0001 GMT, 3 September 1960. The large variations in the values of temperature

Photograph by W. Shackleton

PLATE I—VIEW OF HALIFAX, YORKSHIRE, LOOKING NORTH-WEST,
22 DECEMBER 1957
(see p. 50)



Photograph by W. Shackleton

PLATE II—VIEW OF HALIFAX, YORKSHIRE, LOOKING NORTH-WEST,
23 AUGUST 1958
(see p. 50)

Photograph by K. J. Heffernan *Reproduced by courtesy of Journal of Fluid Mechanics*

PLATE III—CLOUD FORMED ON TOP OF A SMOKE PLUME PRODUCED BY A GRASS FIRE

(see p. 50)

PLATE IV—METEOROLOGICAL OFFICE ARCHIVES
(see p. 64)

To face p. 53]

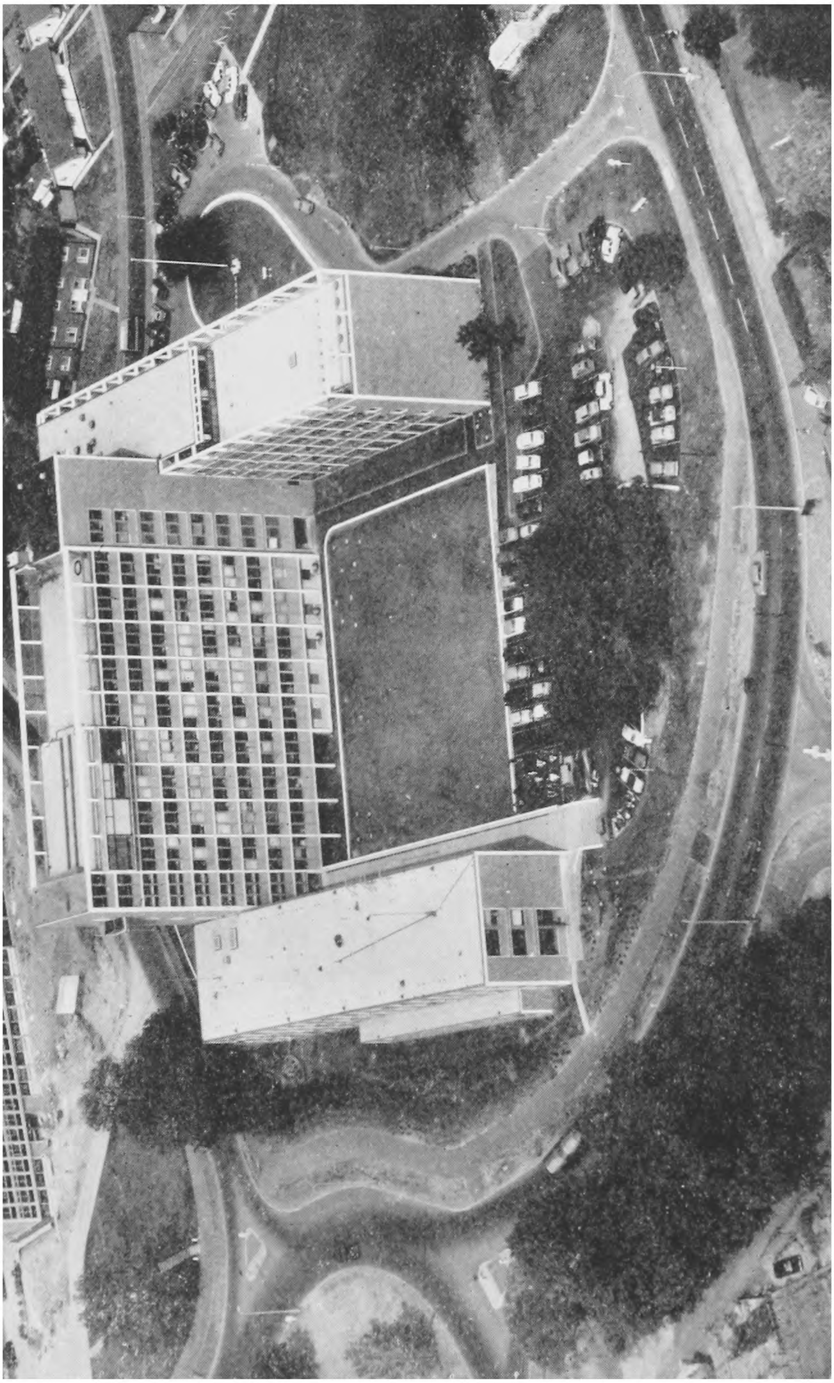


PLATE V—AERIAL VIEW OF THE METEOROLOGICAL OFFICE, BRACKNELL, FROM THE SOUTH-WEST

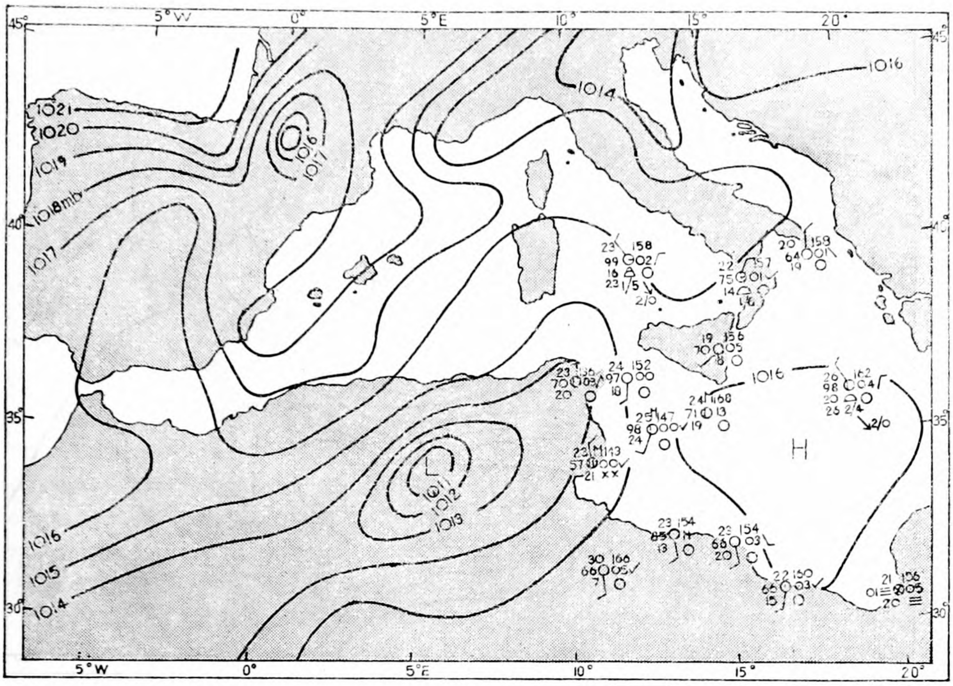


FIGURE 4—SURFACE CHART FOR 0600 GMT, 2 SEPTEMBER 1960

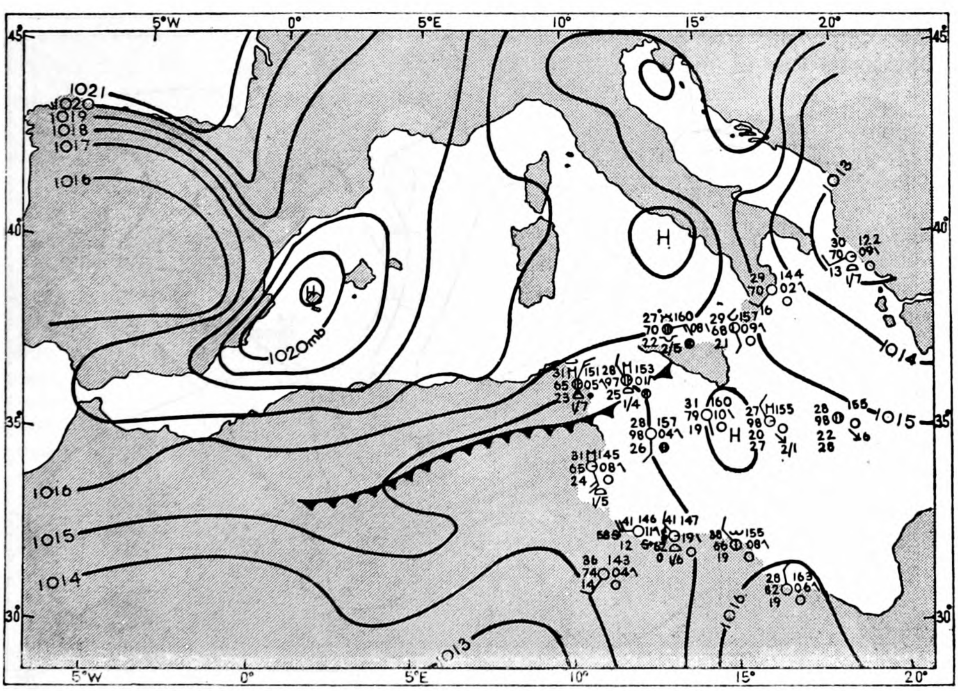


FIGURE 5—SURFACE CHART FOR 1200 GMT, 2 SEPTEMBER 1960

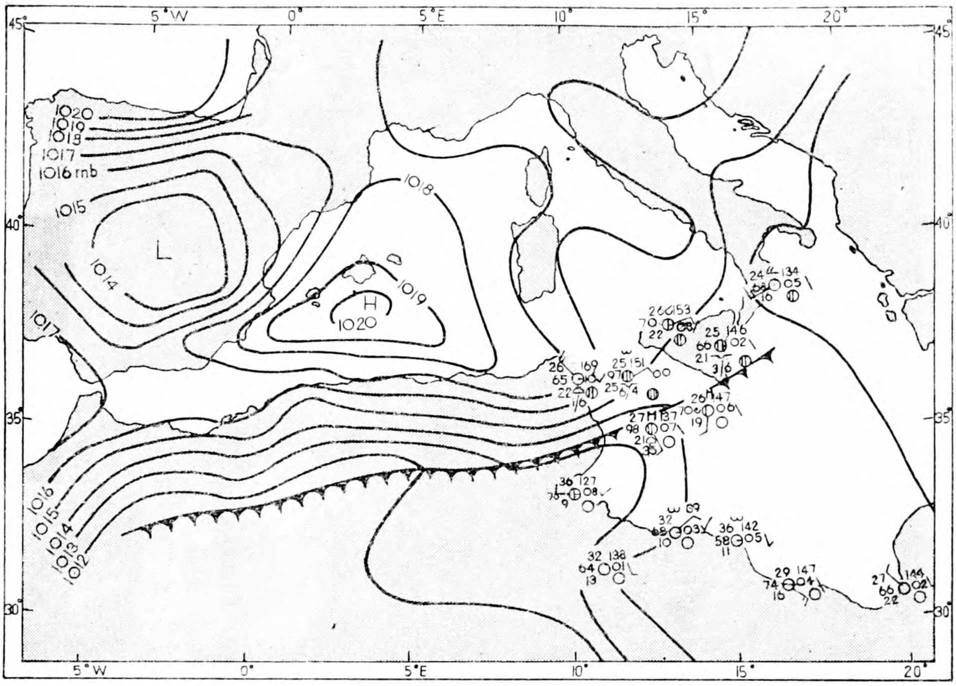


FIGURE 6—SURFACE CHART FOR 1800 GMT, 2 SEPTEMBER 1960

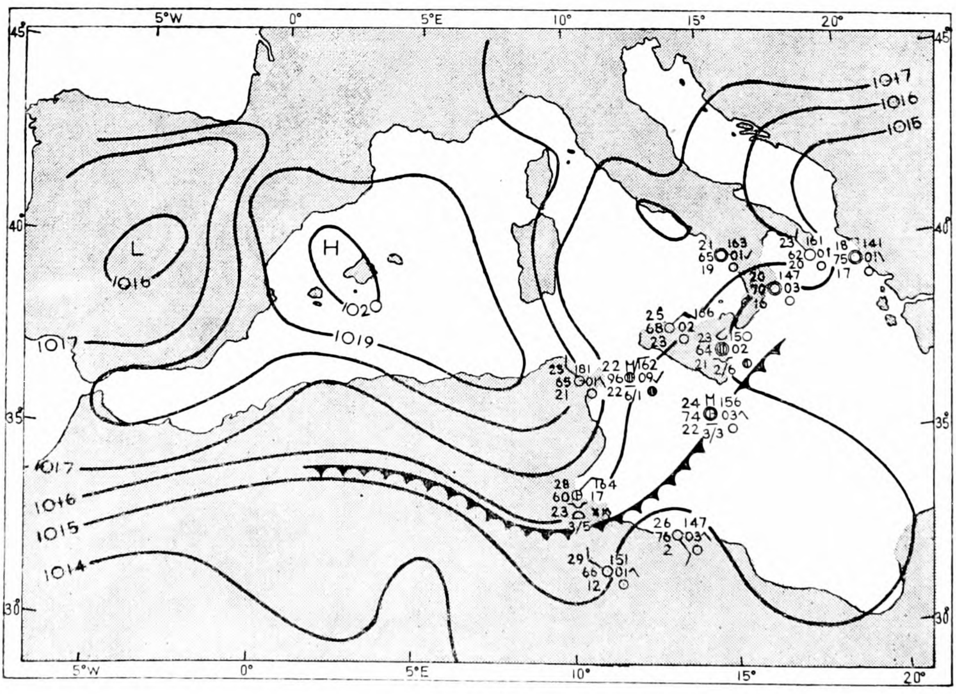


FIGURE 7—SURFACE CHART FOR 0001 GMT, 3 SEPTEMBER 1960

(and dew-point) and wind, combined with the apparent absence of "weather", immediately emphasize the limitations of the surface chart as an aid to the analysis. However, the occurrence of medium cloud of unstable types does suggest instability aloft over Sardinia, the Tyrrhenian Sea and Italy. This is confirmed by the SFLOC reports taken from both the United Kingdom and Mediterranean SFERIC networks and shown in Figures 8, 9 and 10. There is evidently some overlapping in the observations and a probability of position errors but there can be no doubt of the existence of the thunderstorm activity in the areas mentioned. Luqa reported distant lightning flashes to the north-west at 2230 and 2315 GMT. Distant precipitation not reaching the ground was reported to the north-west at 1715, 1745 and 1757 GMT.

Experience has taught the value of the 850 mb chart for depicting conditions near the surface while yet avoiding the complication introduced by many purely local effects. Figures 11, 12, 13 and 14 show the 850 mb charts at 0001 and 1200 GMT on the 2nd and 0001 and 1200 GMT on the 3rd. We recognize at once a weak westerly flow pattern together with isotherms running roughly west to east but with minor wave-like distortions. Although the main temperature gradient is from south to north, it is the minor disturbances moving from west to east in which we are interested. The passage of a very weak discontinuity can be traced at the 850 mb level and it is important to note its close association with the thermal ridge. Behind the discontinuity, the flow was one of cold advection and both thermal trough and ridge slowly increased in amplitude. The temperature at Elmas dropped steadily on the 850 mb charts in the sequence 18°, 16°, 15° and 12°C; that at Malta rose from 21° to 23°C before the discontinuity, then fell sharply to 15°C at 1200 GMT on the 3rd consistent with the presence of the sharp thermal trough.

The wind ascents at Malta (Table I) show that at 850 mb the trough did not pass Malta until 0001 GMT and the radiosonde ascents, Figures 15, 16 and 17 confirm that the main temperature fall in the lower layers occurred after 0001 GMT and before 1200 GMT.

TABLE I—UPPER WINDS AT MALTA, 2 AND 3 SEPTEMBER 1960

		2 September 1960 GMT						3 September 1960 GMT			
Height	Pressure	0500		1100		1700		0001		0500	
ft	mb	degrees	kt	degrees	kt	degrees	kt	degrees	kt	degrees	kt
2000		283	6	210	7	290	15	—	—	320	7
3000	900	300	7	230	9	310	13	260	4	280	6
5000	850	300	11	270	21	290	14	260	11	280	16
7000	750	—	—	290	24	280	16	270	24	290	23
10,000	700	300	25	300	22	290	25	270	33	290	26
14,000	600	290	29	300	27	280	30	270	33	280	35
18,000	500	310	21	280	21	290	30	280	38	290	36
24,000	400	310	19	260	24	270	36	290	39	290	41
30,000	300	260	24	250	33	270	36	270	33	290	41
35,000	250	250	46	240	63	240	63	260	63	270	47
40,000	200	250	67	240	69	240	73	250	72	260	65
47,000	150	240	68	250	59	250	57	240	66	260	57
53,000	100	260	37	240	42	260	34	250	33	260	31
60,000	70	—	—	—	—	290	16	300	9	—	—
Max. wind		240	70	240	78	240	75	260	73	250	67
Height of max. wind (feet)		39,756		40,250		36,740		34,500		42,996	

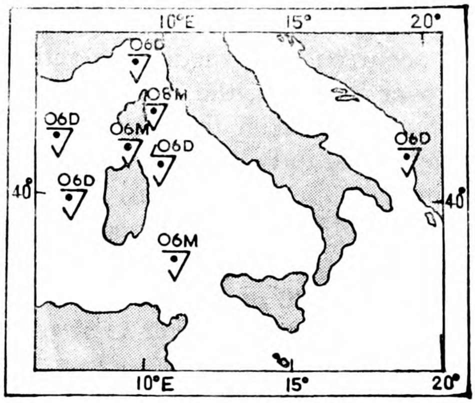


FIGURE 8—SFLOCS 0600–0800 GMT, 2 SEPTEMBER 1960

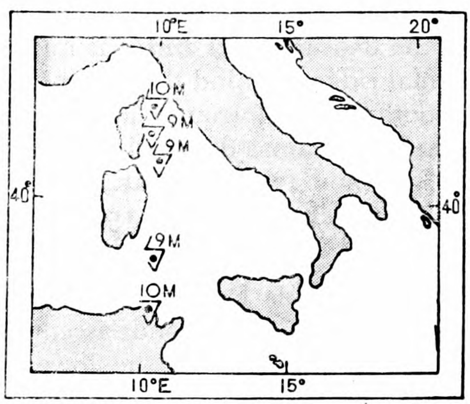


FIGURE 9—SFLOCS 0900–1000 GMT, 2 SEPTEMBER 1960

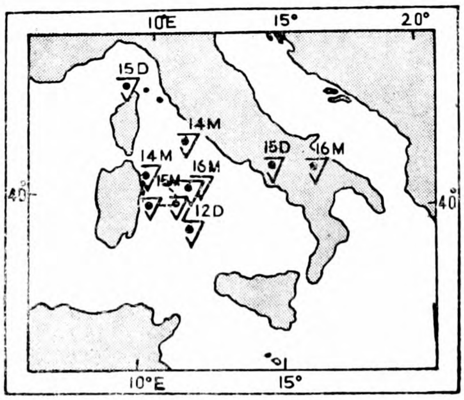


FIGURE 10—SFLOCS 1200–1600 GMT, 2 SEPTEMBER 1960

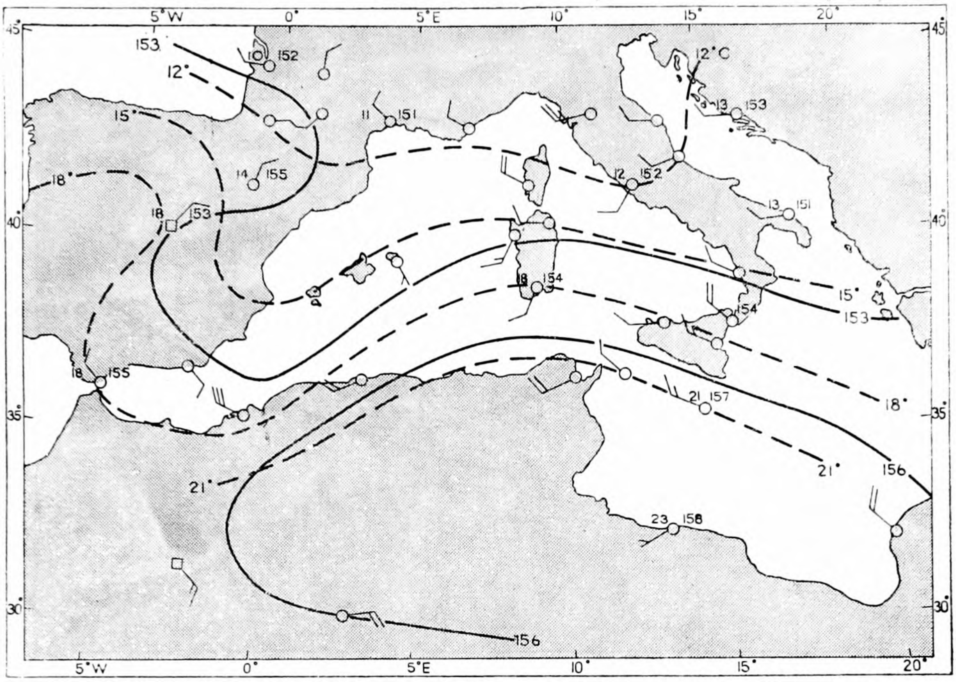


FIGURE 11—850 MB CHART FOR 0001 GMT, 2 SEPTEMBER 1960
The 850 mb contours are in geopotential decametres

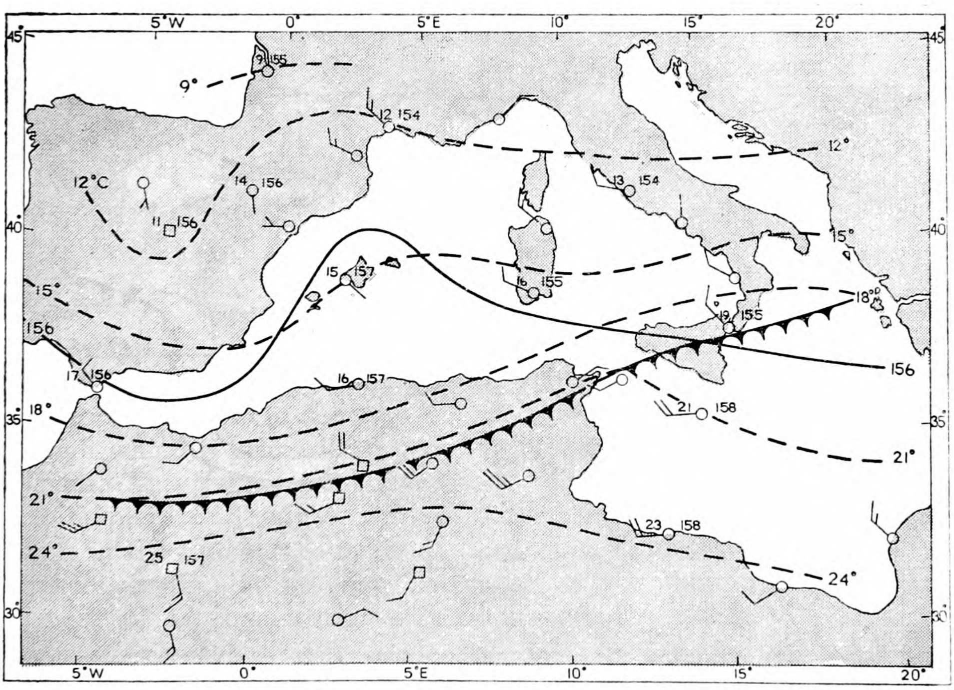


FIGURE 12—850 MB CHART FOR 1200 GMT, 2 SEPTEMBER 1960
The 850 mb contours are in geopotential decametres

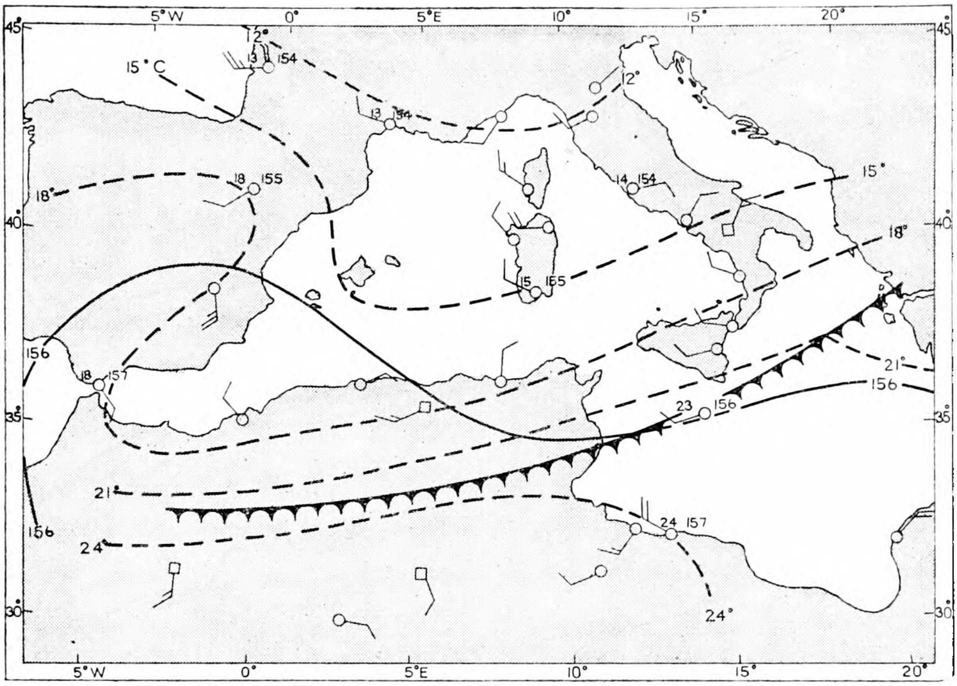


FIGURE 13—850 MB CHART FOR 0001 GMT, 3 SEPTEMBER 1960

The 850 mb contours are in geopotential decametres

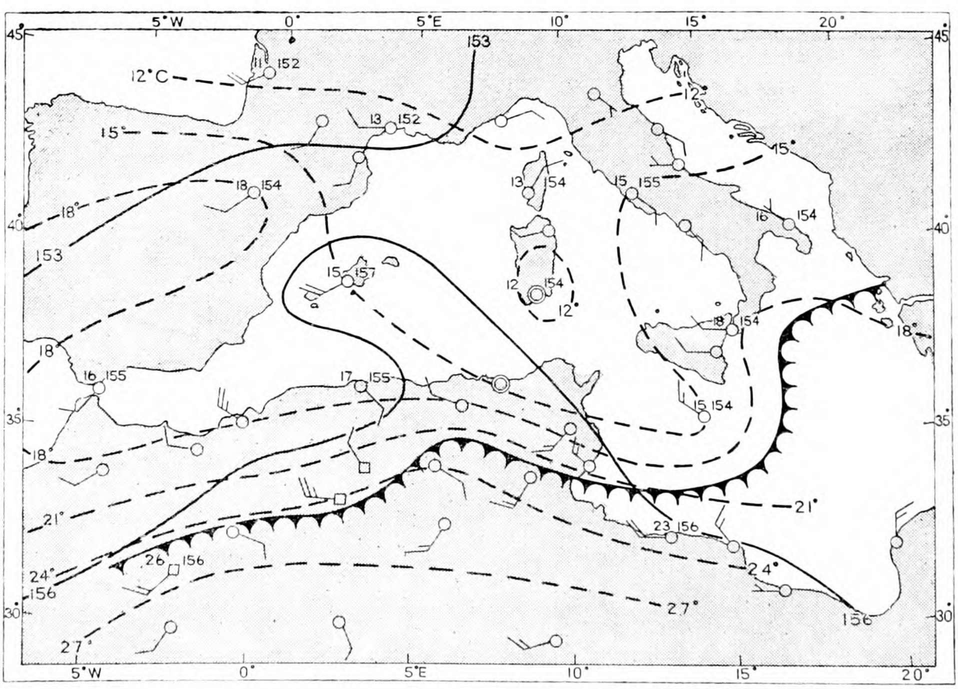


FIGURE 14—850 MB CHART FOR 1200 GMT, 3 SEPTEMBER 1960

The 850 mb contours are in geopotential decametres

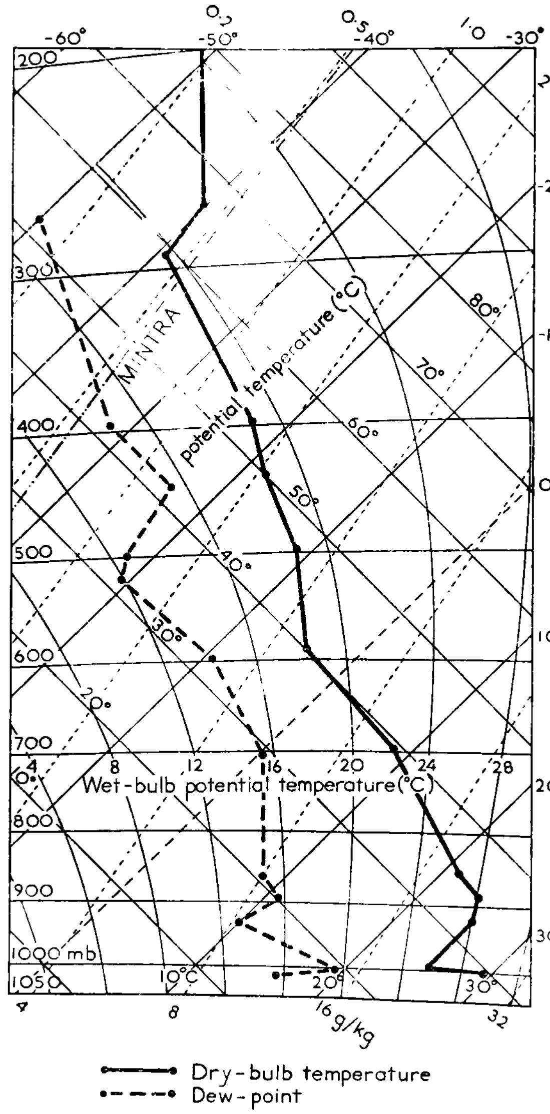


FIGURE 15—UPPER AIR ASCENT AT MALTA FOR 1200 GMT, 2 SEPTEMBER 1960

An examination of the 700 mb and 500 mb charts adds little to the information already available at 850 mb, but the 300 mb charts (Figures 18, 19, 20 and 21) are significant in showing the eastward movement of a pronounced cold trough which is primarily responsible for the perturbation of the flow at lower levels. This is typical of conditions at this time of year and the example serves to emphasize the great utility of the 300 mb chart as representative of conditions in the upper troposphere and also the fundamental importance of disturbances at this level. The association of the thunderstorms and the cloudiness with the upper cold trough is immediately evident.

The evidence shows that the main trough aloft did not pass Malta until after 0001 GMT on the 3rd. The pressure jump which occurred much earlier cannot therefore, in this instance, be directly related to the passage of this upper trough although the possibility remains of an indirect connection

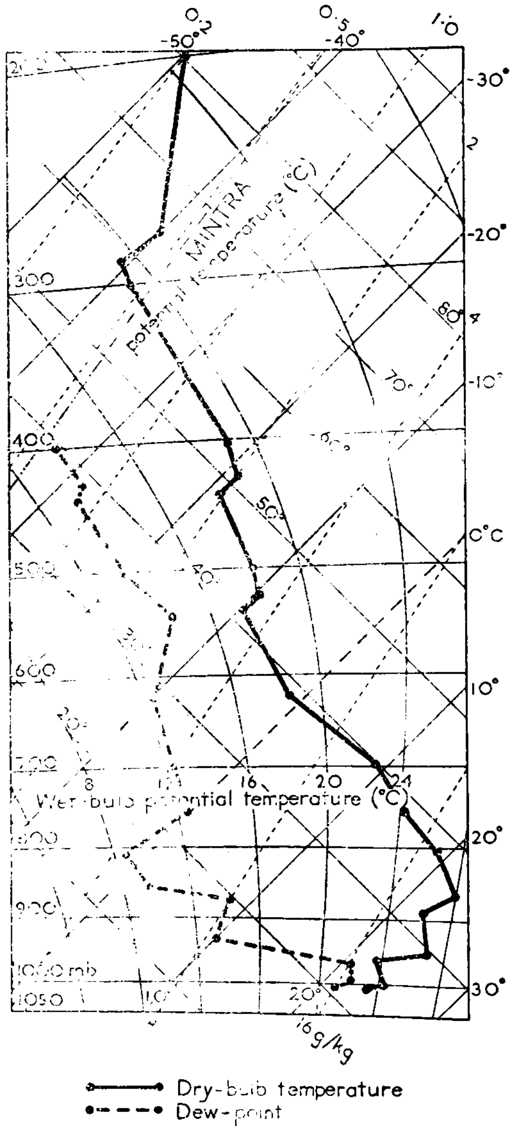


FIGURE 16—UPPER AIR ASCENT AT MALTA FOR 0001 GMT, 3 SEPTEMBER 1960

through the agency of the thunderstorm activity. We can also, following Tepper,[2] seek an explanation in terms of a modification of the low-level inversion although this effect must have been confined to levels below 850 mb. An observation at 1800 GMT of "distant precipitation not reaching the ground" to the north-west of Malta suggests the passage of an instability line and the pressure jump may be evidence of this at Malta.

For want of adequate information we shall, in this instance, ignore the problem of the origin of the pressure jump and confine ourselves to the observation that it would seem to be of direct significance in an appreciation of the situation. Knowledge of its occurrence from the barograph would have been the most positive evidence available of the imminent approach of cooler air and hence of the possibility of patches of low stratus.

The main fall of temperature at the 850 mb level occurred after 0001 GMT on the 3rd although the ascent at that time did show a slight cooling of the inversion below this level. It would be inappropriate, however, to refer to the

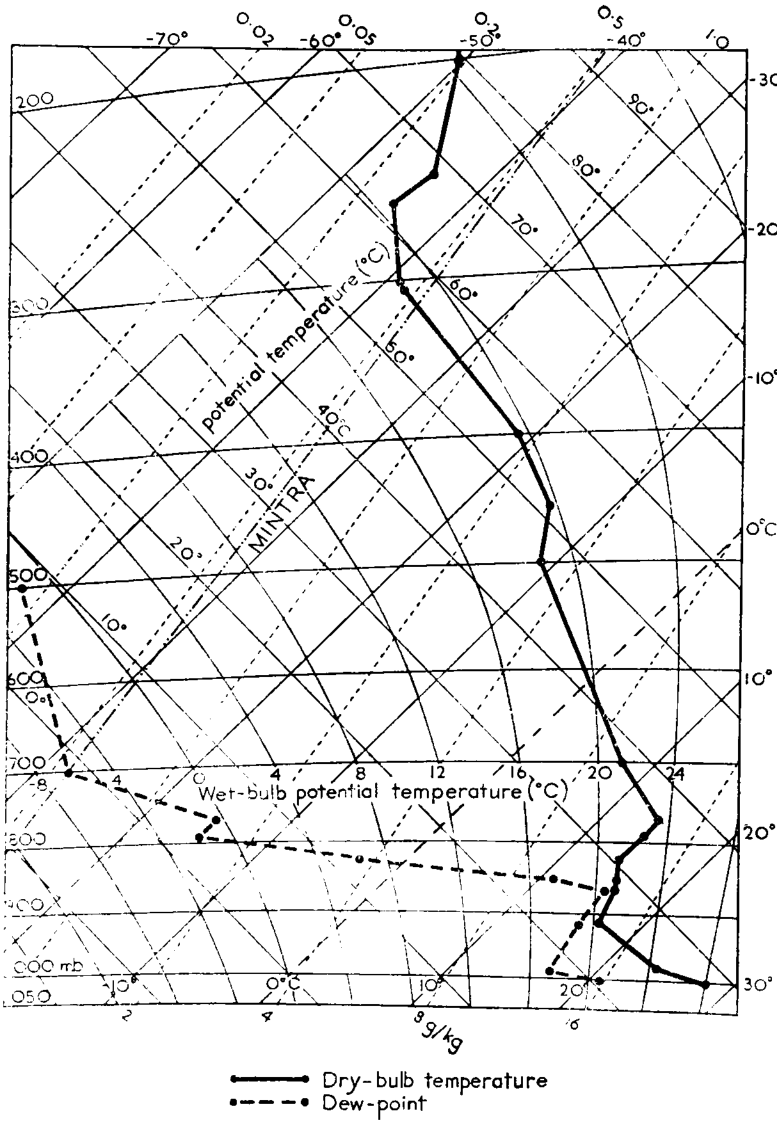


FIGURE 17—UPPER AIR ASCENT AT MALTA FOR 1200 GMT, 3 SEPTEMBER 1960

passage of a cold front; rather would it seem preferable to speak of a "discontinuity in the temperature advection field" or an "advection discontinuity".

The following observations find some illustration in the above example:

(i) Successful analysis in the Mediterranean depends, to a far greater extent than in temperate latitudes, on close attention to detail.

(ii) In the Mediterranean area, particularly in summer and the transition seasons, events on the meso-scale may be larger than those normally regarded as suitable for synoptic analysis.

(iii) In the transition seasons, strong low-level temperature gradients exist, particularly near the low-level inversion. Disturbances of this temperature field are associated with the west to east movement of troughs and ridges in the high troposphere.

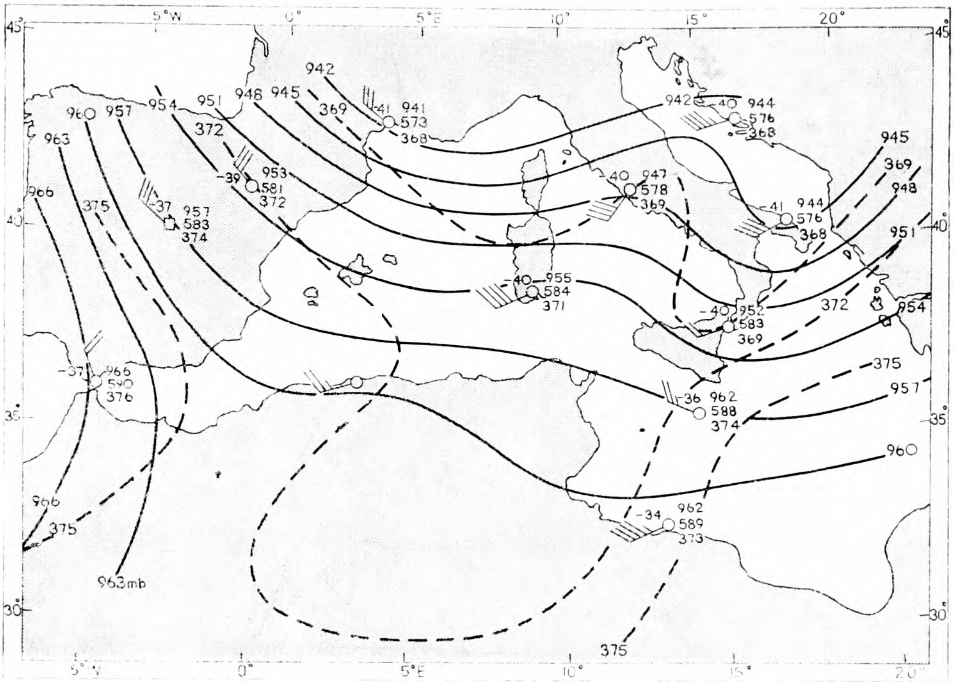


FIGURE 18—300 MB CONTOURS AND 500–300 MB THICKNESS LINES FOR 0001 GMT, 2 SEPTEMBER 1960

Both contour heights and thickness values are in geopotential decametres

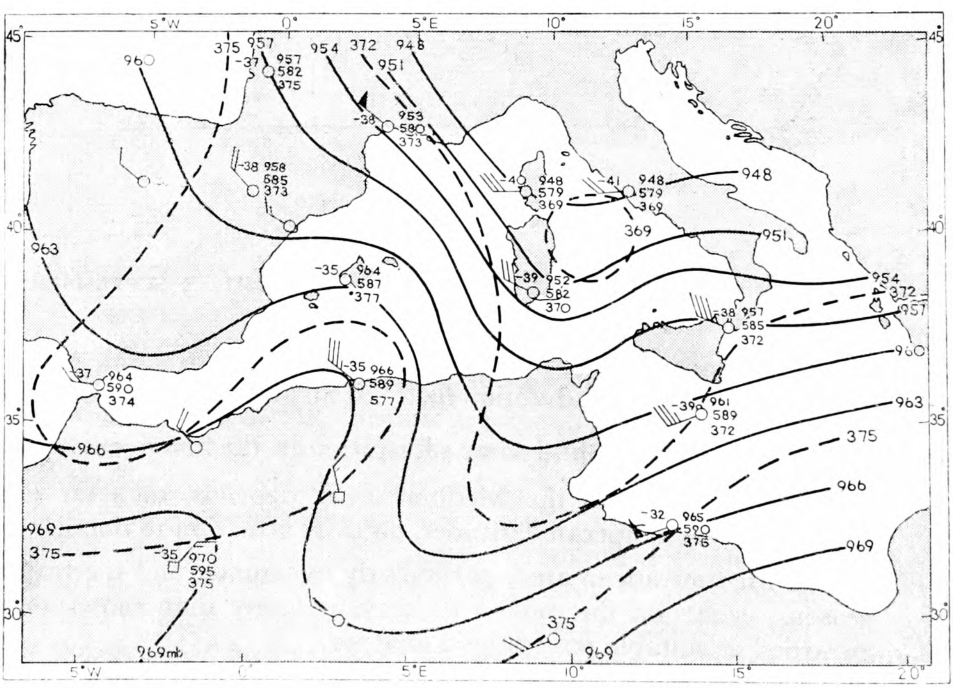


FIGURE 19—300 MB CONTOURS AND 500–300 MB THICKNESS LINES FOR 1200 GMT, 2 SEPTEMBER 1960

Both contour heights and thickness values are in geopotential decametres

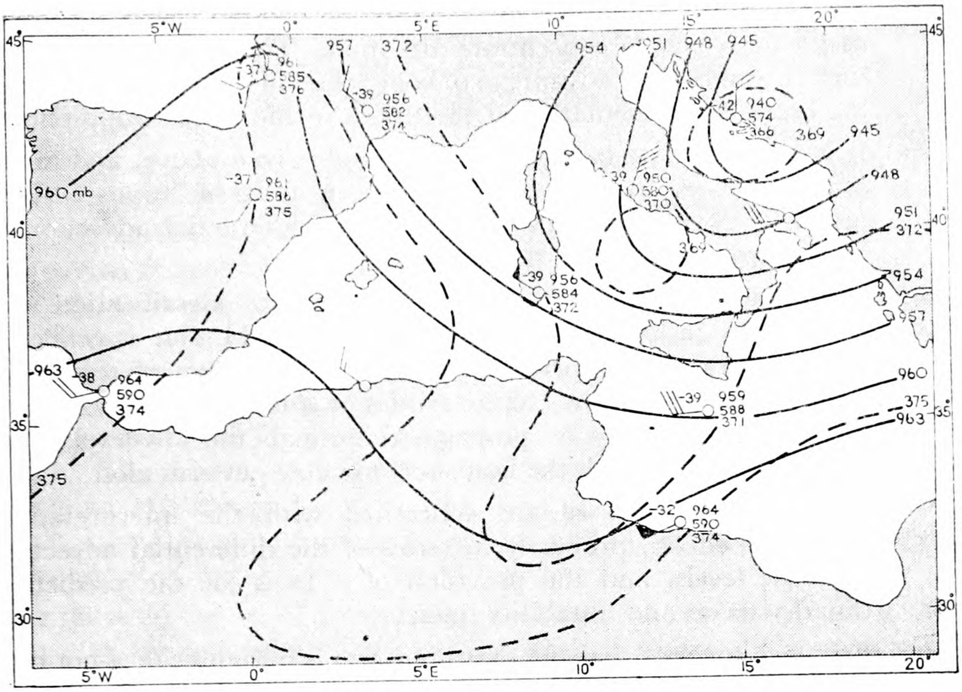


FIGURE 20—300 MB CONTOURS AND 500–300 MB THICKNESS LINES FOR 0001 GMT, 3 SEPTEMBER 1960

Both contour heights and thickness values are in geopotential decametres

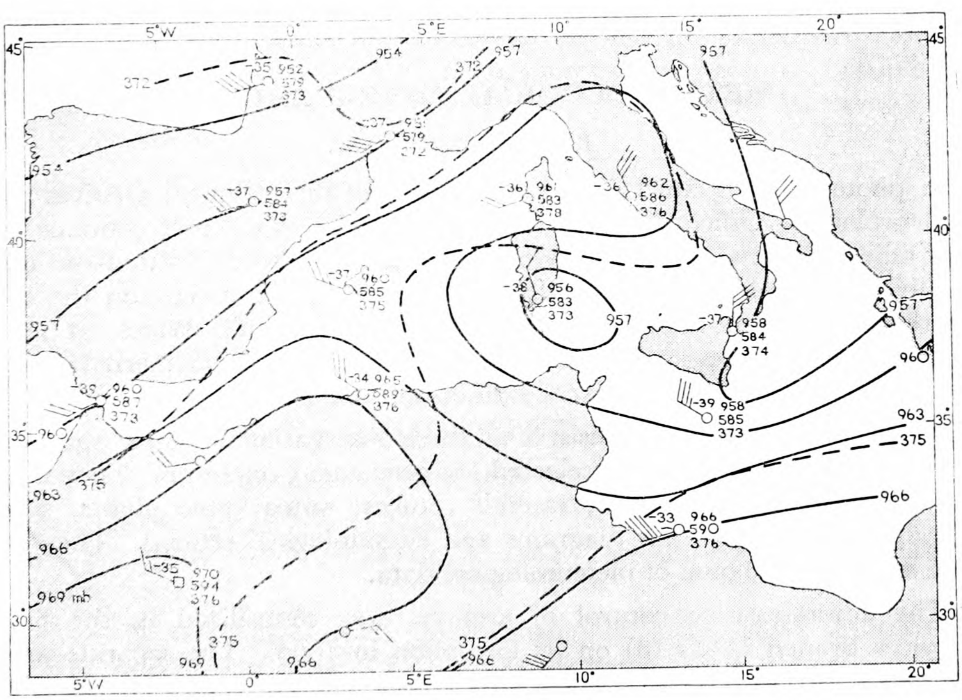


FIGURE 21—300 MB CONTOURS AND 500–300 MB THICKNESS LINES FOR 1200 GMT, 3 SEPTEMBER 1960

Both contour heights and thickness values are in geopotential decametres

(iv) For this type of situation, the 850 mb and 300 mb charts are the most useful on which to concentrate attention. The former is near to the surface and has the advantage of being close to the low-level inversion; the latter is representative of conditions in the upper troposphere.

(v) It is inappropriate in the type of example given above, and in many other instances, to attempt an analysis in terms of "fronts". We are primarily concerned with the analysis of differential advection both in the horizontal and in the vertical.

In the horizontal, the analysis aims at the identification of discontinuities in the temperature advection field that is, effectively, discontinuities of temperature gradient rather than of temperature. These have some of the characteristics of true fronts but, contrary to the latter, they may be propagated through the low-level pressure field in sympathy with the faster-moving flow patterns aloft.

In the vertical, we are concerned with the interpretation of instability effects, primarily in terms of the differential advection at different levels, and the provision of a basis for the prediction of thunderstorms and instability lines.

(vi) Evidence suggests that the pressure jump is of significance not only in meso-scale problems but also on the synoptic scale. Further examples are necessary to demonstrate this.

REFERENCES

1. KIRK, T. H.; "Pressure jumps" at Malta. *Met. Mag., London*, **90**, 1961, p. 206.
2. TEPPER, M.; A proposed mechanism of squall lines: the pressure jump line. *J. Met., Lancaster, Pa.*, **7**, 1950, p. 21.

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METEOROLOGICAL OFFICE ARCHIVES

By G. A. BULL B.Sc.

The photograph (Plate IV) shows a corner of the technical archives hall at Meteorological Office, Eastern Road, Bracknell. This hall contains on its two miles of specially built shelving the technical records created—to use the archivist's convenient term—by meteorologists and observers, on the staff of or reporting to the Meteorological Office, in England, Wales, at sea and overseas. The corresponding archives for Scotland and Northern Ireland are housed at Meteorological Offices Edinburgh and Belfast, respectively.

These technical records consist of all those observational records and working documents which have been selected for permanent retention. They contain, for example, daily registers, rainfall returns, autographic charts, synoptic working charts, upper air diagrams and climatological returns. They constitute a great storehouse of meteorological data.

The administrative control of archives was centralized in the Support Services Branch (M.O.18) on its formation in 1960. The separate archival collections of a number of branches previously held at Victory House, Harrow, and Dunstable were brought together in the archives hall in the Instruments and Storage building at Eastern Road, Bracknell, on its completion in the spring of 1962. They are cared for by a small staff which constitutes M.O.18e.

A matter of vital importance in the control of archives is the new law on the preservation of public records set out in the Public Records Act 1958 which gave effect to the recommendations of the Government's Committee on Public Records (Grigg Committee) of 1952. New rules for the selection of Meteorological Office documents for permanent preservation and for making those retained available for public use have had to be drawn up as required by the Act, a task in which much help has been received from the Air Ministry Departmental Records Officer and from officials of the Public Record Office. The Act provides that official documents selected for permanent preservation are, in general, to be deposited in the Public Record Office but a clause permits the Lord Chancellor, the Minister responsible for public records, to appoint places of deposit outside the Public Record Office for particular classes of archives, provided facilities similar to those of the Public Record Office are available. The Meteorological Office has been appointed a place of deposit following an application based on the need of public users to have expert guidance in studying meteorological records and on the great usage made of them by the staff in public services and research.

Some notes on the use of archives may be helpful to readers. Queries which may involve the use of archives will be dealt with by the branch of the Meteorological Office specializing in the subject of the inquiry (for example, M.O.3 for queries relating to climatology) and the specialist branch will advise the inquirer as to the records he needs to use. Space is available in the archives office for visitors to examine records with which they are concerned or the records may be transferred to the main building for use under the guidance of the specialist branch. The building containing the archives is a few minutes' walk from the main building eastwards along London Road. It will readily be understood that these original records cannot be lent by the archives staff for use away from the Meteorological Office premises. It is, however, possible for photographic copies to be made under the terms specified in Meteorological Office Leaflet No. 2.

A walk round the archives' shelves is an impressive experience. Here are ships' logs collected by Admiral FitzRoy, there are the rainfall returns made by the voluntary observers of Symons's British Rainfall Organization or the synoptic charts drawn by the early forecasters. In this hall set in the new headquarters buildings, one has a deep sense of the collective effort of the meteorologists and observers of the past.

METEOROLOGICAL OFFICE DISCUSSION

Forecasting dry and wet spells

The first Meteorological Office discussion of the winter season was held at the Royal Society of Arts on 15 October 1962. The subject was "Forecasting dry and wet spells".

Mr. C. A. S. Lowndes opened the discussion by giving some statistics on dry spells of three days or more at Kew for the six months from May to October. Most of the spells were associated with a spread of high pressure from the south-west or west of the British Isles. The essence of this model was the development of a slow-moving meridional type of upper flow pattern with a ridge over the British Isles. The requirements for the setting up of the model were a strong mobile upper trough over the western Atlantic and a surface anticyclone in the Azores region. Successful forecasting rules were based on measurements of upper troughs between 60°W and 50°W and the surface pressure at Horta in the Azores. Mr. Lowndes continued with some statistics on five-day wet spells at Kew. The wet spells were often associated with a slow-moving upper trough in the region of the British Isles. Successful forecasting rules were based on measurements of upper troughs between 30°W and 10°W, the surface pressure at Valentia or London and the spacing to the next upwind upper trough.

The dry- and wet-spell models both covered about half the spells which actually occurred.

A long discussion followed in which many speakers took part. Mr. V. R. Coles said that forecasters at C.F.O. found Mr. Lowndes's rules most valuable. Prebaratics beyond the 24-hour period were difficult to construct and interpret with confidence and it was useful to have other tests to deal with medium range forecasts.

The Director-General said that he found the subject of particular interest as the Office was always being pressed to extend its forecasts over longer periods. Dry spells were obviously more easy to define and investigate than wet spells. For this reason, the Office, at present, confined its notifications to the general public to dry spells. The assembly of suitable criteria defining various spells which were meaningful to the consumer was important and warnings of wet spells might be required in future.

REVIEWS

Assault on the unknown, by Walter Sullivan. 8½ in. x 5½ in., pp. xiv + 460, *illus.*, Hodder and Stoughton Ltd., 1962. Price: 30*s.*

This book gives an excellent account, by an extremely well informed layman, of most aspects of the International Geophysical Year. Written in a narrative style it relates the conception of the idea, the planning, the frustrations and the execution of the various projects which accumulated in the IGY. The author describes the men as well as their activities, dealing mainly of course with the scientists responsible for and taking part in the events. But he also makes some telling probes into the reactions of the general public (mainly in the United States) and politicians to various aspects of the IGY. After reading this immensely interesting book, one feels more than ever that the international collaboration evinced by the IGY was engendered entirely by scientific co-operation, and that the unity of this international spirit was sufficiently genuine to repress the jingoistic traits of both politicians and general public.

In the preface the author states that the emergence of science as a potent force in international affairs has taken many by surprise. The refreshing spirit of scientific co-operation is emphasized throughout the book. The author emerges as a first class advocate for scientific philosophy, particularly when it breeds this type of social behaviour.

The book is divided into 24 chapters of uneven length. The first four are devoted to the history of effects and ideas leading up to the IGY, and ten are allocated to satellites, rockets and the outer atmosphere. Only one chapter deals with meteorology, partly perhaps because it has less appeal to the public imagination; however, this subject does tend to overlap into some of the following six chapters, two each on the Arctic, Antarctic and oceanography. Two short chapters deal with seismology and gravimetry. The final chapter is entitled "The harvest", which largely speaks for itself; however the author is inclined to regard the harvest as one of international co-operation as an end in itself (marred by the regrettable stolen satellite incident). The true harvest should rather be an increase in scientific knowledge. For this reason we must hope that the very great effort and perseverance that went into the IGY, and is so well described in this book, will be matched by a similar effort in the analysis of data and the dissemination of results in the near future.

G. B. TUCKER

Tables of Normalized Associated Legendre Polynomials, by S. L. Belousov. 10¼ in. × 7 in., pp. 379, *illus.*, Pergamon Press, Headington Hill Hall, Oxford, 1962. Price: £7.

The Legendre polynominals arise naturally in the representation of a function in spherical co-ordinates, just as do Fourier series for a periodic function. In the latter case the functions necessary for computation are the sine and cosine and are, of course, tabulated as a function of a single variable. The Legendre polynomials are functions of three variables; textbooks give the formal expressions for functions and explicit expressions in the simplest cases but the functions have not been exhaustively tabulated.

The functions will clearly arise in representing any geophysical field near the earth's surface, and meteorologists may be particularly interested in representing fields such as contour heights, temperature etc. over a wide domain. The author of the tables, who is well known for his dynamical work in meteorology, found that it was necessary to extend considerably the tabulation of the functions in order to represent features of the size of depressions; he used an electronic computer to carry out the tabulation.

This volume is a translation from the original Russian text published in 1956. There is a careful account of the methods of computation used and of the possible errors. The main bulk of the book is the tabulation of $\overline{P_n^m}$ (cos θ) for $m = 0(1)\ 36$, $n = 1(1)56$ and $\theta = 0(2.5)\ 90°$ to six decimal places; no differences are given. The printing and layout seem to be adequate, though only a user could testify to this and also to the accuracy of the tables. Perhaps most possible users will have an electronic computer available and will compute such functions when they are needed in the course of a calculation. The tables will be most valuable to the occasional user who does not have the use of a computer.

E. KNIGHTING

HONOUR

We note with pleasure the election of Professor H. Amorim Ferreira, C.B.E., Director of the Portuguese Meteorological Service, to the Presidency of the Portuguese National Academy of Sciences for the year 1963.

METEOROLOGICAL OFFICE NEWS

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

Mr. T. Herrod, Senior Experimental Officer, who retired on 10 November 1962 after over 25 years' service.

Mr. Herrod joined the Meteorological Office as an Assistant II at Sealand in 1937. He served at stations in northern England until 1945, during which time he was promoted to Assistant I. He was mobilized in the Royal Air Force as a Flight Lieutenant from September 1942 until November 1945. On demobilization he was assimilated as a Senior Experimental Officer, and served in Malta from February 1946 until August 1947. He subsequently spent 13 years at Shawbury and Preston, followed by a two-year tour of duty at Aden before his retirement.

Mr. R. J. Williams, M.B.E., Senior Experimental Officer, who retired on 31 October 1962 after 43½ years' service.

Mr. Williams left his home area (Barmouth) in 1919, at the early age of 16½ years, to come to London to join the Office as a Probationer. He spent all his career at Headquarters, including nine years as personal assistant to the late Sir Nelson Johnson (then Director of the Meteorological Office).

It is fair to say that it was while he was with Sir Nelson that Mr. Williams made his mark in the Office. During these nine years, which included World War II and consequently the handling of large numbers of important papers, Mr. Williams acquired a fund of knowledge on administration in the Air Ministry and other Departments which he was always ready to pass on to his colleagues. In the same way his experience in organizational and financial matters pertaining to the Office has been of great value on many occasions.

Problems and difficulties presented to him by colleagues visiting Headquarters, particularly during and after World War II, were listened to sympathetically and, if Mr. Williams could assist, he did not spare himself in doing so.

It was inevitable with Sir Nelson's great activity in international affairs, particularly those of the International Meteorological Organization (later World Meteorological Organization), that Mr. Williams should become involved also. He therefore played a considerable part in assisting with the arrangements for such conferences as the IMO Conference of Directors (1946) and the Commonwealth Meteorological Conference (1946).

Mr. Williams is spending his retirement in his native land and in the area he knew well as a boy. He has decided to settle in Arthog, a village on the south side of the Mawddach estuary opposite Barmouth. With the departure of "Taffy" Williams, the Office has indeed said farewell to an individual who will be greatly missed, particularly by those at Headquarters.

C.W.G.D.

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STELLAR SCINTILLATION

By J. BRIGGS

Introduction.—The stars are seen to scintillate or twinkle, that is, their apparent brightness fluctuates rapidly. To the layman this behaviour is merely intriguing but for the astronomer the effects are a nuisance. The inconstant illumination of the stellar image makes observing more difficult and, at times, the accompanying spreading and jumping of the image is so severe as to cause the abandonment of observations. For this reason the subject has been investigated from time to time and the findings of these investigations have meteorological implications.

To the unaided eye scintillation appears as a brightness variation but in the telescope of the astronomer the intensity variations are less obvious than the blurring and jumping of the image which is partially due to phase scintillation, that is, to phase changes in the incoming light. Both phase and intensity scintillations are manifestations of the same phenomenon. By the eye the frequency of the fluctuations can be estimated as one to 10 cycles per second but the use of light-sensitive instruments of low time-constant reveals fluctuations of between one and 1000 cycles per second.

The intensity of scintillation decreases as the star rises above the horizon which suggests that by far the greater part of the effect is a function of the depth of the earth's atmosphere traversed by the incoming light. Other factors may be involved and, indeed, a physiological explanation was once put forward, but it is now well established that the scintillation is due to local fluctuations in the refractive index of air which, at the wavelengths of visible radiation, depends only on air density and, hence, on air temperature, pressure and water-vapour pressure. For the visible wavelengths the effect of vapour pressure is small in comparison with those of temperature and pressure. As the wavelength increases the refractive index of air ceases to be dependent only on density, and other factors are introduced which increase the effect of vapour pressure, and at radio wavelengths the effect becomes important. Pressure changes are also probably unimportant except for changes on a scale so large and hence so slow that the effects would not be recognized as scintillation. Thus the variation of refractive index which causes the scintillation is mainly due to small-scale temperature fluctuations. These fluctuations are a manifestation of the turbulence of the air and it may be that study of the facts of scintillation can lead to increased knowledge of atmospheric turbulence.

Stellar shadow patterns.—The refractive index of air changes, more or less regularly, with variation of time, height and distance but in addition there exist small sudden changes due to convective mixing or to turbulence. These local changes cause small deviations about the mean path of a beam of starlight and two neighbouring beams which have slightly different mean paths will encounter slightly different deviations so that, after passing through a turbulent layer, the two beams will tend to converge or to diverge as they approach the ground. Thus, at some places on the ground an intensification of illumination will be produced whilst other places will have decreased illumination. The result is patchy distribution of relatively light and dark areas which is called the "shadow pattern" of the star. The size of the elements in the shadow pattern is related to the size of the disturbing eddies, and the dominant eddy size will determine the scale of the shadow pattern. Since the atmospheric irregularities are always changing the shadow pattern is in constant movement.

The shadow pattern may be seen if the eye is placed behind a diaphragm in the focal plane of a telescope, pointed toward a bright star, and the eye focused on the objective. If the eye is replaced by a light-sensitive cell connected to suitable magnifying circuits then fairly precise quantitative observations of the shadow pattern are possible.

The arguments of geometrical optics have been used above in accounting for the shadow pattern formation. Theoretical treatments of scintillation based on geometrical optics, or on approximations to wave theory, have been given by several writers, notably Bergmann,[1] Chandrasekhar[2] and van Isacker.[3] These treatments are useful so long as the turbulent elements concerned are large in comparison with the wavelength of light; also the depth of the turbulent layer must not be too big. If the conditions for validity of simple geometrical theory are not satisfied then diffraction effects have to be considered and the turbulent layer must be regarded as a large irregular diffracting screen in the manner first followed by Booker, Ratcliffe and Shinn.[4]

In general the turbulence concerned is mild and the corresponding diffraction "grating" is weak. The problem can then be treated as one in which the shadow pattern is due to interference between the undeviated light, i.e. most of the light, and the deviated light. When the turbulence is more severe and more of the incident light is scattered, then the single scattering approach is no longer tenable and a more complicated multiple scattering theory is required. The single scattering approach has been used by a number of writers notably Ellison,[5] van Isacker,[6] Megaw[7] and Scheffler.[8] Multiple scattering has been treated by van Isacker,[3] Keller[9,10] and by Keller and Hardie.[11]

Using the weak-grating approximation to diffraction theory, an expression can be obtained, see Keller,[12] for the relation between the spectrum function of the amplitudes of refractive index fluctuations and the corresponding function of the amplitude of fluctuations of illumination at the ground, thus:

$$\frac{F(L)}{(\text{mean light intensity})^2} \propto \frac{d f(L) \sin^2 (\pi z \lambda / L^2)}{\lambda^2}, \quad \ldots (1)$$

where $F(L)$ = spectrum function of the squares of the amplitudes of the Fourier components of the refractive index fluctuations,

$f(L)$ = corresponding function for the illumination fluctuations,

L = wavelength of the particular component of the shadow pattern,
λ = wavelength of the light,
z = mean height of the turbulent layer,
d = thickness of the layer,

The theory assumes the turbulence to be isotropic. This is reasonable since the largest eddies are unlikely to produce effects recognizable as scintillation and the smallest eddies are usually isotropic even if the turbulence as a whole is not.

When $\pi z\lambda/L^2$ is small the above expression reduces to

$$\frac{F(L)}{(\text{mean light intensity})^2} \propto \frac{d\, z^2 f(L)}{L^4} \quad \ldots (2)$$

This expression is derivable from geometrical theory. The effective value of z is the distance along the light path between the turbulent layer and the observer and thus increases in proportion to the secant of the zenith distance so that $\pi z\lambda/L^2$ is not small, and the expression (2) is not valid, for large zenith distances.

Expression (2) shows no dependence on λ which implies that there is little or no colour scintillation for stars near the zenith; this is in accord with observations made by Mikesell, Hoag and Hall[13] and by Protheroe.[14]

Both d and z increase in proportion to the secant of zenith angle (x). Thus near the zenith, when expression (2) applies, the mean square amplitude of the scintillation should vary as $\sec^3\chi$. If expression (1) applies it may be shown that the mean square amplitude should vary as $\sec x$. Observational data have been used to check the expressions in this way, e.g. van Isacker,[6] Protheroe[14] and Scheffler.[8] Good support for the expressions is found although there is a fair amount of scatter.

Using a multiple-scattering theory, van Isacker[3] obtained an expression for the spectrum of the Fourier components in the spatial variation of light intensity in the shadow pattern. This treatment involves a number of approximations and assumes that the turbulent layer is thin so that the light wave is phase-modulated only. It is also necessary to assume that the layer is at a height large in comparison with the size of the largest turbulent element. Keller[10] obtained results which agree with those of van Isacker though avoiding some of the approximations used by van Isacker; on the assumption that the auto-correlation function of the density fluctuations is isotropic and Gaussian, Keller computes spectra of intensity fluctuations in the shadow patterns.

The relation of scintillation to atmospheric turbulence.—Although it is well established that atmospheric turbulence is the primary cause of scintillation it is not clear whether the whole atmosphere or only part is involved. The use of ultra-rapid thermometers shows small-scale turbulence to be present at all heights and times in the troposphere and lower stratosphere; it seems reasonable to suppose that all these layers are involved in the production of scintillation. However, it is important to realize that there is a focusing effect involved. This effect is shown in expression (2), where the amplitude of the shadow spectrum produced by a turbulent layer is seen to be proportional to the square of the height of the layer. The focusing effect may be explained by the fact that the convergence, or divergence, of neighbouring light beams which is produced by atmospheric variations is very small so that, if the layer involved is near the ground, then the difference between the beams at the ground is extremely small and true scintillation is not produced, although some image spreading occurs which is associated with bad astronomical "seeing" conditions. Great heights are ruled out as effective contributors since the mean density decreases exponentially with height.

There is some evidence, e.g. Mikesell,[15] that poor "seeing" and scintillation are not strongly correlated. Indeed it has been shown that conditions in the telescope itself or near that observatory can contribute to poor "seeing". Butler[16] also records that good seeing and haze go together whilst Ellison[17] states that astronomical seeing is usually better on mountain tops. Experience therefore suggests that poor seeing conditions are due to the lower layers of the atmosphere whereas scintillation is due to the layers in the upper troposphere and lower stratosphere. It must be noted too that temperature fluctuations occur most readily when strong wind shear is combined with non-adiabatic lapse rate, conditions most likely to be well developed in the vicinity of inversion layers and of the tropopause.

Observational comparisons of scintillation and atmospheric conditions.

Size of turbulent element.—Estimates of the size of the elements in the shadow pattern can be made by comparing the effects of the planets with those of the stars. Since a planet subtends a relatively large angle compared with the turbulent elements then each point of the planet scintillates like a star but the total light remains steady (Ellison and Seddon[18]). Ellison[17] determined the critical angular diameter for production of scintillation by observation of the planets and their satellites and found the average turbulent element to have an angular diameter of about 3 seconds. Variation of the size of the telescope aperture showed the brightness variation to be greatest with apertures of about 7 cm which suggested the shadow pattern elements to be of this order. The size of the real turbulent element does not necessarily equal that of the shadow pattern element, but Ellison found that the amplitude variations did not fall far below the mean amplitude and so indicated a close correspondence between the sizes of the two elements. Keller[10] used data obtained by Protheroe[14] and Scheffler[8] in a quasi-quantitative analysis based on multiple scattering theory. He accounted for the data by taking the turbulent element size to be 5 to 8 cm with a corresponding root mean square temperature fluctuation of 0.1 to 0.4°C. These values corresponded to a layer thickness of 10 to 40 m but root mean square temperature fluctuations of the order of 0.01°C would also have satisfied the data provided the layer thickness was in the region of 2000 to 4000 m. Keller differentiated between the different scales of temperature fluctuations by comparing the values of root mean square temperature changes produced by adiabatic mixing through the relevant layer thicknesses, and in this way rejected the smaller values of temperature fluctuations (and corresponding thicker layers).

The direction of motion of shadow patterns.—The movement of the shadow pattern across a telescope may be measured by exposing photographic plates in the focal plane of the telescope. Ellison[17] describes such a method. Hosfeld[19] used increasing time exposures and showed that the recorded pattern tended to elongate with increasing exposure duration thus indicating distinct pattern movement. If the telescope objective is stopped down to a rectangular slit, the directional effect of the shadow pattern is also shown since the frequency of the scintillation measured varies with the direction of the slit; low-frequency components are favoured when the slit is parallel to the motion and high-frequency components when the slit is normal to the motion. This effect, discovered by Mikesell, Hoag and Hall,[13] was also used by Protheroe[20] who found strong correlation of the pattern direction with that of the wind at 200 mb. Barnhart, Protheroe and Galli,[21] using dual telescopes, made simultaneous readings of the intensity of illumination at two points in the shadow pattern and found similarity of pattern appearance, combined with a time shift, when the two probes were in line with the pattern movement.

The speed of the shadow patterns.—The dual probe method of Barnhart, Protheroe and Galli[21] gives the velocity of the pattern movement since the time shift between the two observed patterns can be measured. Comparison of the results with radiosonde winds suggests that the altitude of the pattern-producing layer is above 10,000 feet. The pattern velocity has also been determined by examination of the streaks produced on photographic plates though on some nights the results were indeterminate due, possibly, to motion occurring in several layers moving with different velocities (see Ellison[17]).

The height of the turbulent layer.—Correlations between the scintillation and wind velocities at various heights have been reported by a number of workers. In general, the heights of agreement are above 20,000 ft, for example as reported by Gifford and Mikesell,[22] Mikesell,[15] Gifford[23] and Protheroe[20] though Mikesell suggests a correlation with winds at much lower levels, up to 20,000 ft, for the 10 c/sec scintillation. Ellison[17] deduced a height of the turbulent elements of about 2.6 km from their estimated angular diameter of 3 seconds. Barnhart, Protheroe and Galli[21] compared the dual probe measurements of pattern movement with radiosonde winds and found close association for heights within 8000 feet of the tropopause, though it must be observed that on some nights a very wide height range would have given good agreement. By observing the scintillation of double stars Gardiner *et alii*[24] conclude that the 150 c/sec scintillation is produced at heights of 10,000 to 40,000 feet but the 1 to 10 c/sec scintillation is developed as high as 100,000 feet.

The quantitative analysis by Keller,[10] using data by Protheroe[13] and based on the multiple scattering theory, gives a height between 8 and 15 km for the turbulent layer and a corresponding layer thickness of between 10 and 40 m.

Keller[25] also showed that the average spatial autocorrelation function of the shadow pattern is related to the average root mean square deviation of the combined brightness of the star, observed simultaneously by two telescopes. Protheroe[14] simplified this method by using a single telescope of large aperture and an objective diaphragm with two relatively small holes. On the measurements for three nights he deduced shadow pattern movements which agreed closely with the winds at 200 mb as shown by contour charts. Barnhart, Keller and Mitchell[26] developed this autocorrelation method using two telescopes and an automatic correlation computer. They found that on some nights there were several possible altitudes of agreement as regards wind direction and direction of shadow pattern movement but that as regards velocity no more than two altitudes of agreement were possible. Combination of direction and velocity generally gave a unique altitude of agreement between 12 and 14 km (the tropopause varied between 11 and 15 km). The method also indicated spectra of pattern element sizes and showed the dominant turbulent element to be between 15 and 30 cm.

Summary.—The experimental evidence strongly suggests that the temporal variations of scintillation at a fixed point are largely due to the translation of fixed shadow patterns across the line of sight. Furthermore, the correlations obtained with wind observations suggest that the important layers are those in the high troposphere and low stratosphere although the temperature fluctuations observed might indicate that all the layers of the troposphere are contributory.

Megaw[7] has suggested that optical and radio measurements are more readily explained by an everchanging multi-layered model than by a few-layered model. It must be noted that on occasions the experimental data fit the winds at several heights and, of course, the winds at different levels are highly inter-correlated. If a multi-layer model were involved it might be expected that a mean wind over a deep section of the atmosphere would correspond to pattern movement; certainly on occasions such a mean wind, excluding surface layers, would fit the data reasonably well.

Temperature fluctuations are usually biggest in inversion layers. It may be that, in general, the amplitude of fluctuation is negligible as regards scintillation and only when the layer is high (for maximum focusing effect) and corresponds to an inversion layer (for greatest amplitude) does the variation of illumination become significant.

The high frequency of the scintillation calls for some comment. On a single-layer theory the observed frequencies correspond to turbulent elements of about 10 cm (for example, if the wavelength of shadow pattern is L, the frequency is f and the wind speed at the turbulent layer is V, we then have $L = V/f$; a reasonable value for V is 25 m/sec so that if f is 100 c/sec then $L = 25$ cm). It is difficult to visualize elements on this scale as having temperature fluctuations as large as the 0.1 to 0.4°C required by single-layer theory. The more probable order of fluctuation of temperature on this scale is 0.01°C. Keller found that this order of fluctuation required a much thicker layer, of thousands rather than tens of metres, but then rejected this solution since adiabatic mixing through such a thick layer produces root mean square temperatures greatly in excess of the prescribed temperature fluctuation. This rejection seems somewhat arbitrary since the size of the eddies causing the temperature fluctuations may be considerably less than the full depth of the turbulent layer. It may be that the turbulent elements are an order or so larger, say one metre or more, and the high frequency of scintillation due partly to the interaction of a limited number of relatively thin turbulent layers.

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WINDS AT THE 200 MB LEVEL OVER THE TROPICS AND SUB-TROPICS DURING THE SEASONS OF MONSOON CHANGE

By J. G. LOCKWOOD, Ph. D.

Introduction.—In Geophysical Memoirs No. 103 (Upper Winds over the World)[1] mean upper air charts were published for the midseason months, January, April, July and October. In temperate latitudes the changes in the upper flow patterns (except at very high levels) between the midseason months are gradual, and it is therefore possible to obtain approximate means for the remaining months by simple interpolation. There are, however, two complete reversals of the 200 mb flow during the year in parts of the tropics. This can be seen by comparing the 200 mb average wind charts for January and July in Geophysical Memoirs No. 103. These reversals normally occur in May or June and in October, and take place within a period of a few weeks. They coincide with the advance in May and the retreat in October of the south-west monsoon over southern Asia. Hence it is impossible in the tropics to obtain mean winds for these transitional months by simple interpolation between the charts for midseason months.

To supplement Geophysical Memoirs No. 103, mean charts have been prepared to cover the two transitional periods in the tropics. Because the changes are completed in periods of less than one month it is desirable to prepare these charts for ten-day periods. The reversal of the 200 mb flow is most marked over Ethiopia and Sudan, and southern Asia. Over the tropical central Pacific and South America winds appear to be normally light, but there is a serious lack of data for these areas. The charts are limited to the area 20°W–180°E, 40°N–40°S, within which the wind reversal is most prominent.

The mean charts in Geophysical Memoirs No. 103, were mainly based on the five-year period 1949–53. At most tropical stations, regular upper air observations to 200 mb were only started during the late 1950's. Even during this period many ascents failed to reach 200 mb. Therefore it was decided to use the seven-year period 1954–60 for computing the means for the present charts. This allowed an adequate sample of observations to be obtained from many tropical stations.

The mean wind charts were mainly constructed from the wind observations. Ten-day mean 200 mb contour charts were also constructed, and these were taken into account when constructing the mean wind charts except within about 15° of the equator. There was some difficulty in drawing reasonable streamline-isotach patterns over equatorial regions. This was partly due to a lack of data and partly to the charts covering a transition which may vary in date from year to year.

The transition in May and June.—The main features of the 200 mb wind fields shown on the ten-day average charts for May and June (Figures 1 to 6) are as follows:

(*a*) the northern hemisphere subtropical westerly current,

(*b*) the equatorial easterly currents and

(*c*) the southern hemisphere subtropical westerly current.

There is one small scale feature shown on the charts:

(*d*) the Wake Island–Johnston Island westerly current.

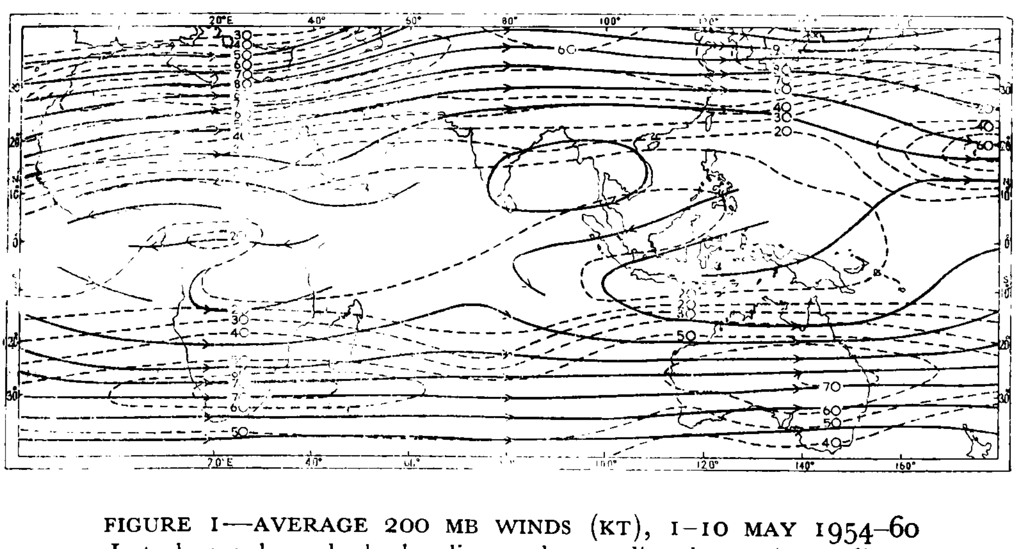

FIGURE 1—AVERAGE 200 MB WINDS (KT), 1–10 MAY 1954–60
Isotachs are shown by broken lines and streamlines by continuous lines.

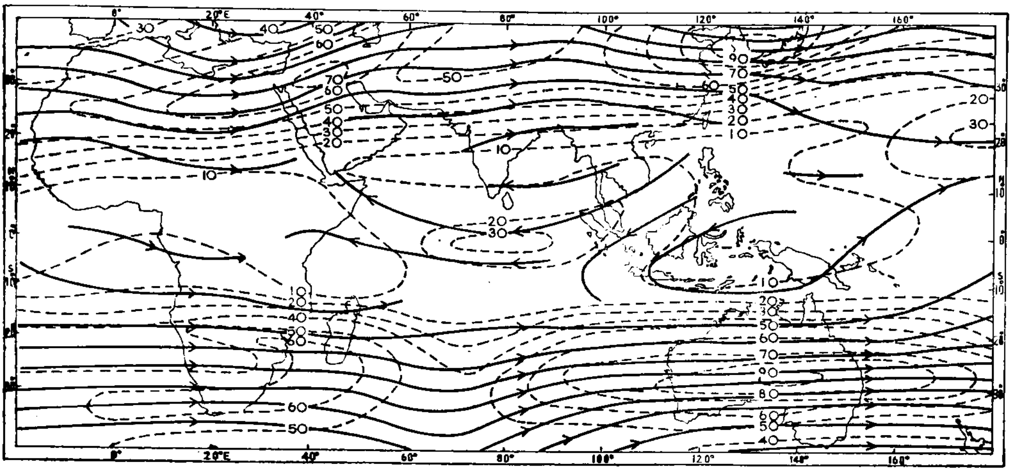

FIGURE 2—AVERAGE 200 MB WINDS (KT), 11–20 MAY 1954–60
Isotachs are shown by broken lines and streamlines by continuous lines.

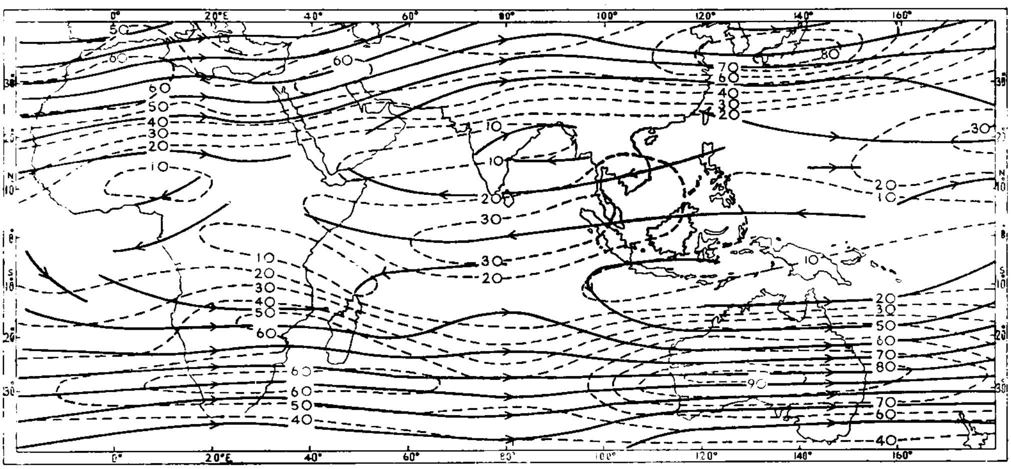

FIGURE 3—AVERAGE 200 MB WINDS (KT), 21–30 MAY 1954–60
Isotachs are shown by broken lines and streamlines by continuous lines.

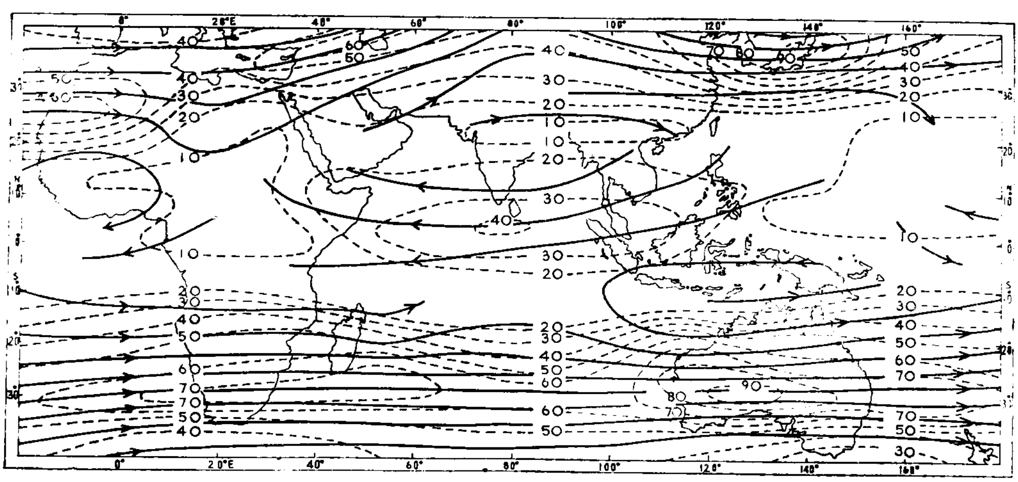

FIGURE 4—AVERAGE 200 MB WINDS (KT), 31 MAY–9 JUNE 1954–60
Isotachs are shown by broken lines and streamlines by continuous lines.

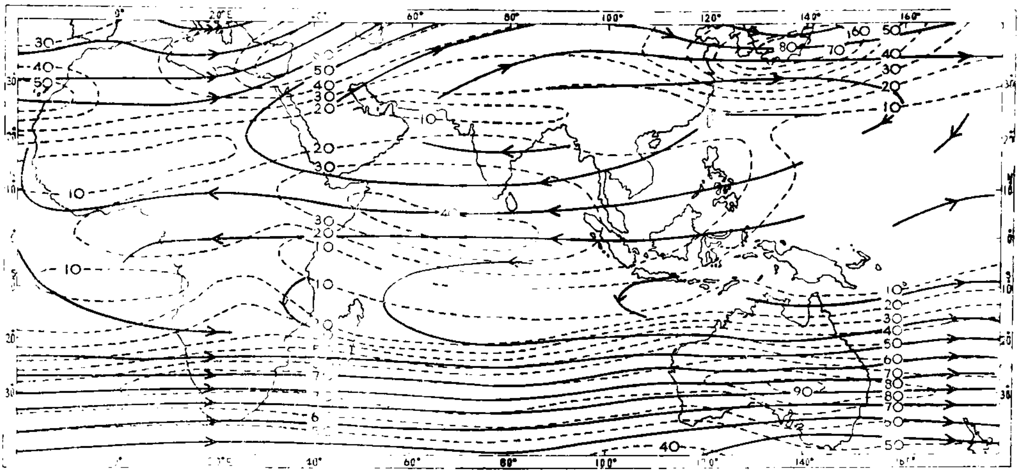

FIGURE 5—AVERAGE 200 MB WINDS (KT), 10–19 JUNE 1954–60
Isotachs are shown by broken lines and streamlines by continuous lines.

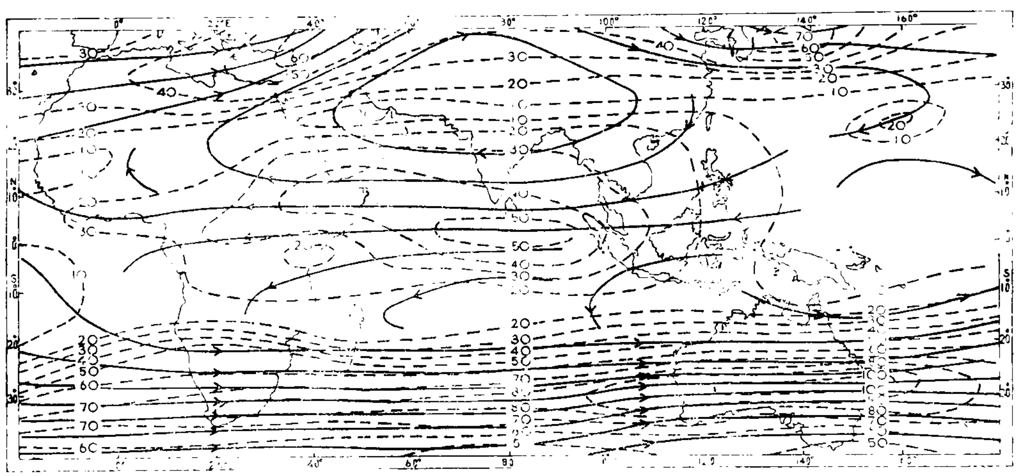

FIGURE 6—AVERAGE 200 MB WINDS (KT), 20–29 JUNE 1954–60
Isotachs are shown by broken lines and streamlines by continuous lines.

The northern hemisphere subtropical westerly current.—This current extends from North Africa to the central Pacific throughout the period. It is divided into two sections with high average wind speeds, one centred over North Africa and the Middle East, and the other over Japan. At the beginning of May (Figure 1) the western maximum, represented by the isopleth for 80 knots, extends from the western Sahara to Iran. For most of May the jet axis continues with the same alignment but the speed decreases, especially over Africa. During June this maximum moves north-west to Asia Minor, with unchanging speed.

The maximum of the subtropical westerly current over Japan undergoes little change in position during May and June. It is associated at first with high average wind speeds, sometimes above 100 knots in the centre. The westward extent of the jet maximum across China is uncertain.

It was first demonstrated by Yin (1949)[2] that the "burst" of the Indian south-west monsoon is connected with the disintegration of the subtropical jet stream over northern India, and the formation of a new jet to the north of the central Asiatic highlands. Graphs of the daily 200 mb zonal wind components at New Delhi and Jodhpur are reproduced in Figure 7. The disintegration of the jet at these two stations is indicated, except in 1956, by the decreasing values of the zonal components. In 1956 the westerly jet left north-west India before 1 May. The date (see Table I) of the disintegration of the westerly jet over India varies within a period of about six weeks.

TABLE I—LAST FIVE-DAY PERIOD IN SPRING WITH A 200 MB WESTERLY JET* OVER NORTH INDIA

Year	Pentad
1955	21–25 May
1956	Before 1 May
1957	21–25 May
1958	5–9 June
1959	16–20 May

* Winds in core above 60 kt.

The equatorial easterly currents.—At the beginning of May there are weak easterly winds in equatorial regions over the eastern part of the Indian Ocean and over equatorial Africa. These currents expand rapidly, so that by the end of June they extend from West Africa to the Philippines. Over northern Africa and southern Asia, they spread northwards into areas previously occupied by the southern part of the subtropical westerly current, thus causing a complete reversal of the 200 mb winds. This is shown, for example, by the 200 mb wind records from Khartoum (Figure 7) and Aden (Table II).

TABLE II—DATES OF ARRIVAL OF THE EASTERLY JET AT 200 MB OVER ADEN AND KHARTOUM FOR YEARS 1954–60

Station	Year	Date of last observation with a westerly component	Last five-day period with a mean westerly component	First five-day period with a mean easterly component above ten knots
	1954	29 May	6–10 May	31 May–4 June
	1955	31 May	1–5 May	6–10 May
	1956	12 May	Before 1 May	16–20 May
Aden	1957	8 June	21–25 May	26–30 May
	1958	31 May	Before 1 May	1–5 May
	1959	21 May	11–15 May	26–30 May
	1960	15 May	11–15 May	16–20 May
	1954	6 June	26–30 May	10–14 June
	1955	6 June	31 May–4 June	10–14 June
	1956	25 May	6–10 May	26–30 May
Khartoum	1957	18 June	26–30 May	20–24 June
	1958	11 June	5–9 May	15–19 June
	1959	3 June	21–25 May	10–14 June
	1960	13 June	5–9 June	15–19 June

In May and June the easterly currents spread northwards and replace the westerlies at Khartoum and Aden. The dates of their arrival at these two stations are tabulated in Table II. Three different criteria are used, the date of the last observation with a westerly component, the last five-day period with a mean westerly component and the first five-day period with a mean easterly component above 10 knots. The last normally occurs at Aden in mid-May and at Khartoum in mid-June.

The southern hemisphere subtropical westerly current.—Between 10°S and 40°S a westerly current covers the whole sector included in the mean charts. Because of a lack of data the detailed features of this current are obscure, except over Australia and South Africa. A jet maximum is centred over

Australia at the beginning of May; this remains nearly constant in position but slowly increases in strength towards the end of June. The westerly current over southern Africa slowly increases in strength throughout May and June.

The Wake Island–Johnston Island current.—This is a small westerly current which flows over the central Pacific (about 180°E, 18°N). On the average chart for the first decade in May, the speed in the centre of the current is shown as about 65 knots. The current decreases in strength and moves east during May. At the beginning of June it has moved east of longitude 180°.

The changes in the flow pattern during May and June.—Sutcliffe and Bannon (1954)[3] demonstrated, for the years 1948 to 1953, a time-relationship between the shift of the 200 mb winds from west to east over Aden and Bahrain, the ending of the polar tropopause over Habbaniya and the onset of the south-west monsoon at the Malabar coast of India. Yeh Tu-Cheng, Dao Shih-Yen and Li Mei-Tsuin (1958)[4] have claimed to show that there is an abrupt change in the pattern of the upper tropospheric circulation over the northern hemisphere in June.

In Figure 7 are reproduced graphs of the daily 200 mb zonal winds at Jodhpur, New Delhi and Khartoum. The dates of the start of the south-west monsoon on the Malabar coast (as published by the Indian Meteorological Department[5]) are also noted. In some years the south-west monsoon reached the Malabar coast and then became stationary, or even retreated, and did not start to advance across India until a later date. In these cases two dates are marked. The former is the date of the first advance across the Malabar coast, the latter the start of the true advance across India.

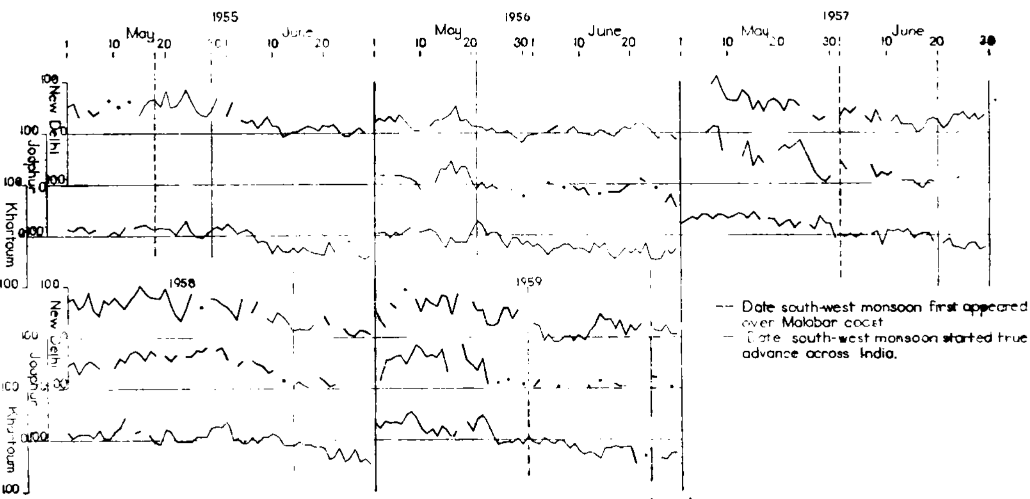

FIGURE 7—DAILY 200 MB ZONAL COMPONENTS (KT) DURING MAY AND JUNE 1955–59, AT NEW DELHI, JODHPUR AND KHARTOUM

Westerly components above the axes, easterly components below the axes.

Figure 7 indicates that in general the strong zonal winds (above 60 knots) associated with the subtropical jet stream left New Delhi and Jodhpur before the start of the main advance of the south-west monsoon across India. In 1955, the ceasing of the strong zonal winds at New Delhi coincided with the start of the main advance of the monsoon.

An inspection of Figure 7, also shows that the main 200 mb easterlies arrived at Khartoum after the start of the south-west monsoon on the Malabar coast. This is in accord with the findings of Sutcliffe and Bannon[3] concerning Aden.

The significant changes in the 200 mb flow patterns during May and June may be considered as taking place in the following order:

(*a*) The first notable change is the movement of the high wind speeds associated with the subtropical jet from the southern to the northern side of the highlands of central Asia.

(*b*) After this change has taken place, the equatorial easterly current expands rapidly northwards, eastwards, and westwards from the central Indian Ocean across southern Asia, central Africa and the western Pacific.

(*c*) Some time after the subtropical jet has left India, and before the 200 mb easterlies become definitely established at Khartoum, the south-west monsoon reaches the Malabar coast of India.

The transition in October.—The main features of the average wind charts for May and June were noted earlier. Except for the Wake Island–Johnston Island westerly current, the same main features are found on the average wind charts for October (Figures 8 to 11).

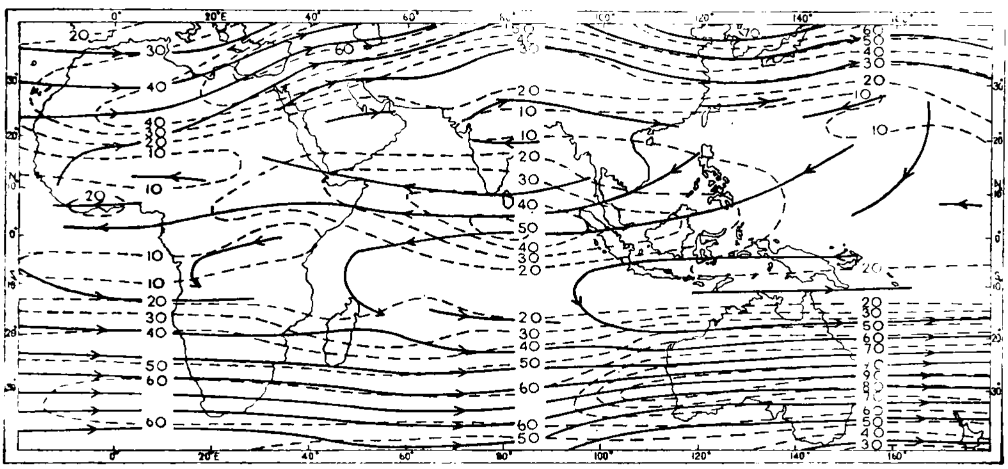

FIGURE 8—AVERAGE 200 MB WINDS (KT), 23 SEPTEMBER–2 OCTOBER 1954–60
Isotachs are shown by broken lines and streamlines by continuous lines.

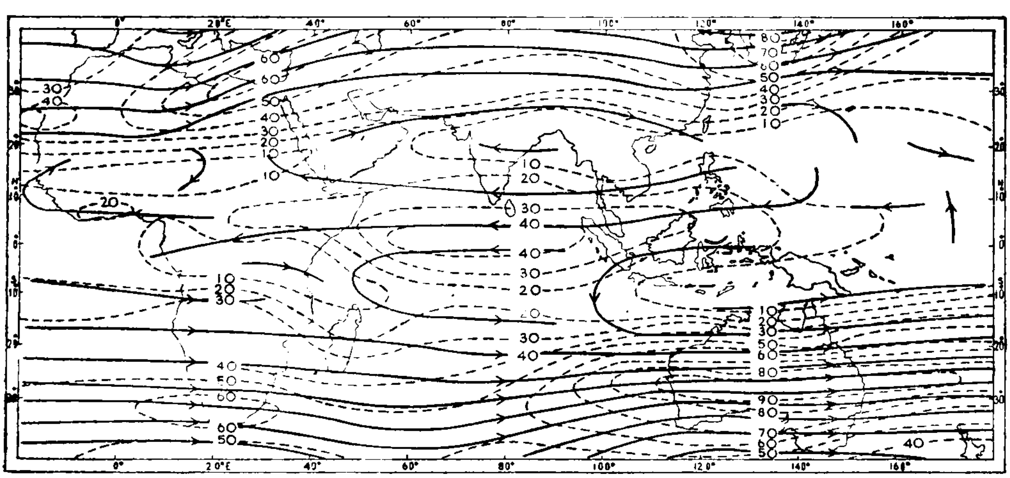

FIGURE 9—AVERAGE 200 MB WINDS (KT), 3–12 OCTOBER 1954–60
Isotachs are shown by broken lines and streamlines by continuous lines.

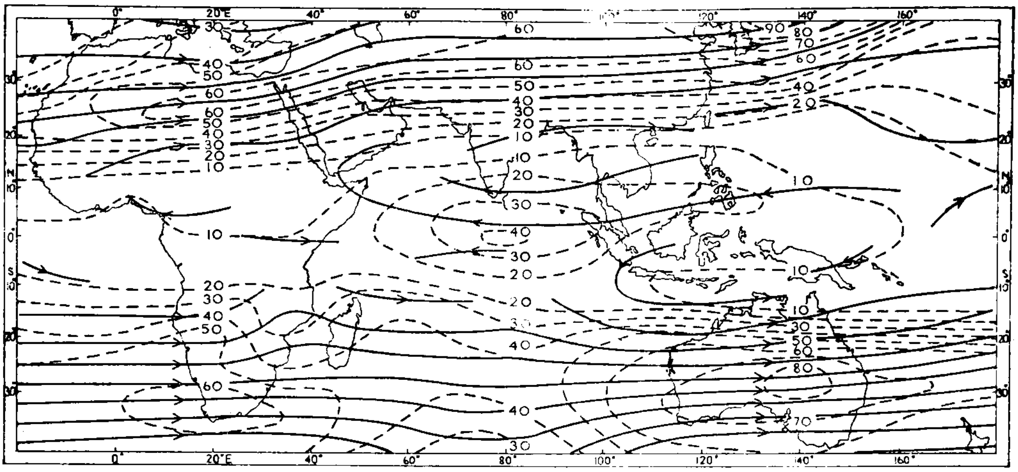

FIGURE 10—AVERAGE 200 MB WINDS (KT), 13–22 OCTOBER 1954–60
Isotachs are shown by broken lines and streamlines by continuous lines.

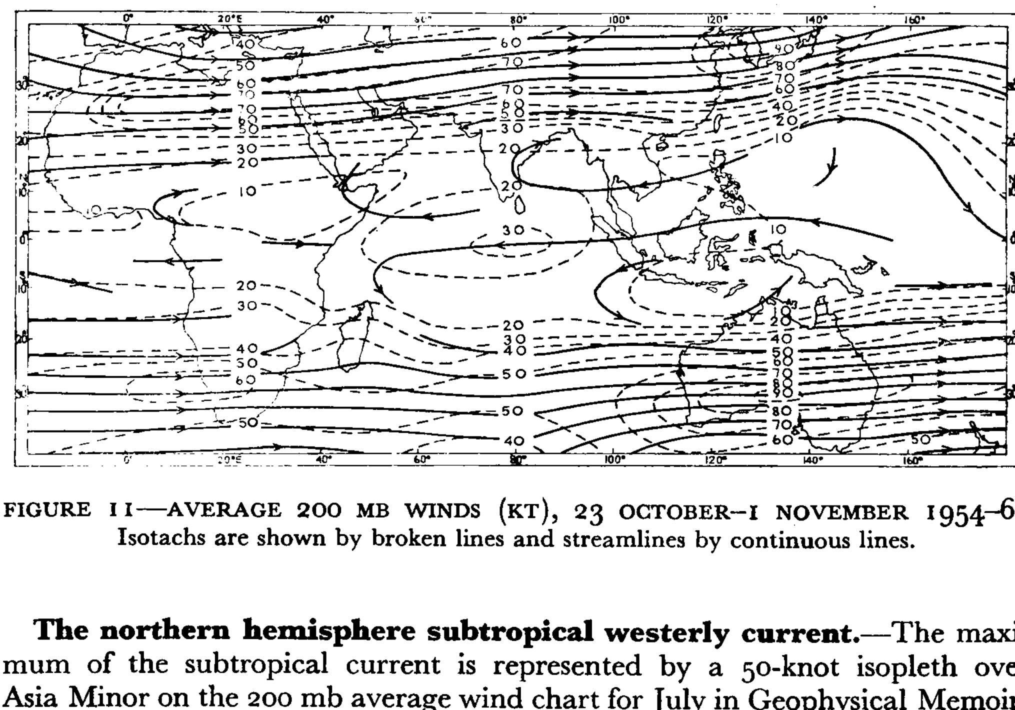

FIGURE 11—AVERAGE 200 MB WINDS (KT), 23 OCTOBER–1 NOVEMBER 1954–60
Isotachs are shown by broken lines and streamlines by continuous lines.

The northern hemisphere subtropical westerly current.—The maximum of the subtropical current is represented by a 50-knot isopleth over Asia Minor on the 200 mb average wind chart for July in Geophysical Memoirs No. 103.[1] Two areas of maximum speed are shown on the average wind chart for 23 September to 2 October (Figure 8), one over the Near East and the other over Japan. The first, represented by the 60-knot isopleth, remains in approximately the same position as the July maximum until the first decade in October. On the chart for the second decade in October (Figure 10), the maximum over the Near East has moved south, and the 60-knot isopleth now encloses an area from the central Sahara to Japan. The chart for the last decade in October (Figure 11) shows the western section of the current roughly in the January position over North Africa, with winds above jet-stream limits (60 knots) over northern India.

Graphs of the daily 200 mb zonal wind components at New Delhi and Jodhpur are reproduced in Figure 12. The dates[5] of the final

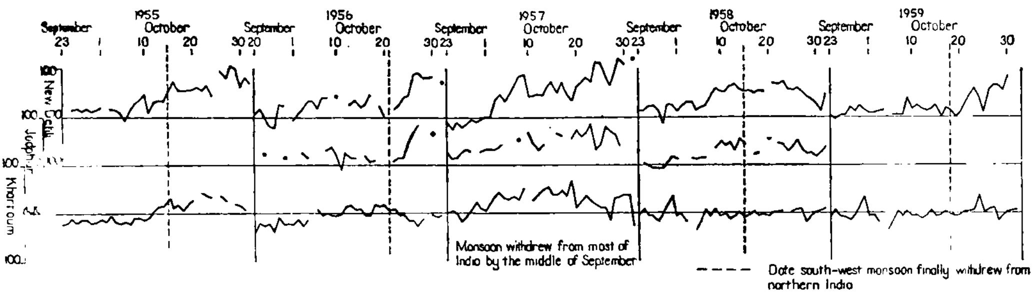

FIGURE 12—DAILY 200 MB ZONAL COMPONENTS (KT) DURING OCTOBER 1955–59, AT NEW DELHI, JODHPUR AND KHARTOUM

Westerly components above the axes, easterly components below the axes.

retreat of the south-west monsoon from northern India are also noted. Except in 1958, strong zonal winds (above 60 knots) associated with the subtropical jet did not become established at New Delhi until after the retreat of the south-west monsoon. In October 1958, the first zonal components above 60 knots at New Delhi occurred a few days before the south-west monsoon left northern India. The relatively sudden increases in the zonal wind speeds at New Delhi and Jodhpur, as the subtropical current forms over northern India, are noteworthy.

The zone of maximum speeds over Japan undergoes little change in position during October. The maximum average speed slowly increases from about 75 knots at the end of September to 95 knots at the end of October.

The equatorial easterly currents.—At the end of September (Figure 8), the equatorial easterly currents extend from West Africa to the western Pacific and reach north to central India and southern Saudi Arabia. This is a smaller area than that covered by the currents on the July average chart.[1] During October the area covered by the currents decreases, until at the end of October they are mostly contained between longtitudes 55°E and 135°E, with the main current over the Indian Ocean to the south of Ceylon. The disintegration of the equatorial currents during October is not as sudden as their formation in May. In May and June there are marked reversals of the 200 mb winds at stations on the border of the growing equatorial currents. These reversals occur again in October, but they are very much less marked than those occurring in May. Graphs of the daily 200 mb zonal components at Khartoum are reproduced in Figure 12; these illustrate the vague change which takes place at a typical station in October.

The southern hemisphere subtropical westerly current.—Between 10°S and 40°S a westerly current covers the average charts for October (Figures 8 to 11). At the end of September there is a wind maximum, indicated by the 90-knot isopleth, over Australia. During October the position of the maximum remains the same, but the wind speed decreases. Over southern

Africa the westerly winds extend slowly north during October, reaching Nairobi by the middle of the month. In November Nairobi had a mean wind of 264°/10 knots (1948–55).[6]

Conclusions.—Over the tropics and subtropics from Africa to the western Pacific, the 200 mb flow patterns can be divided on a climatological scale into two general types. One flow pattern dominates from November to April, and the other from June to September. The average wind charts for January and July in Geophysical Memoirs No. 103,[1] show the two basic flow patterns at their respective greatest developments. The changes in the 200 mb flow pattern in May and June appear to take place in a definite sequence. The October transition is less distinct, but it is still possible to find some order in the sequence of events. The main 200 mb easterly current leaves Khartoum in North Africa before the south-west monsoon retreats from northern India. The south-west monsoon normally retreats from northern India before winds of jet-stream strength (above 60 knots) appear at New Delhi. This would appear to be the reverse of the sequence of events occurring in May and June.

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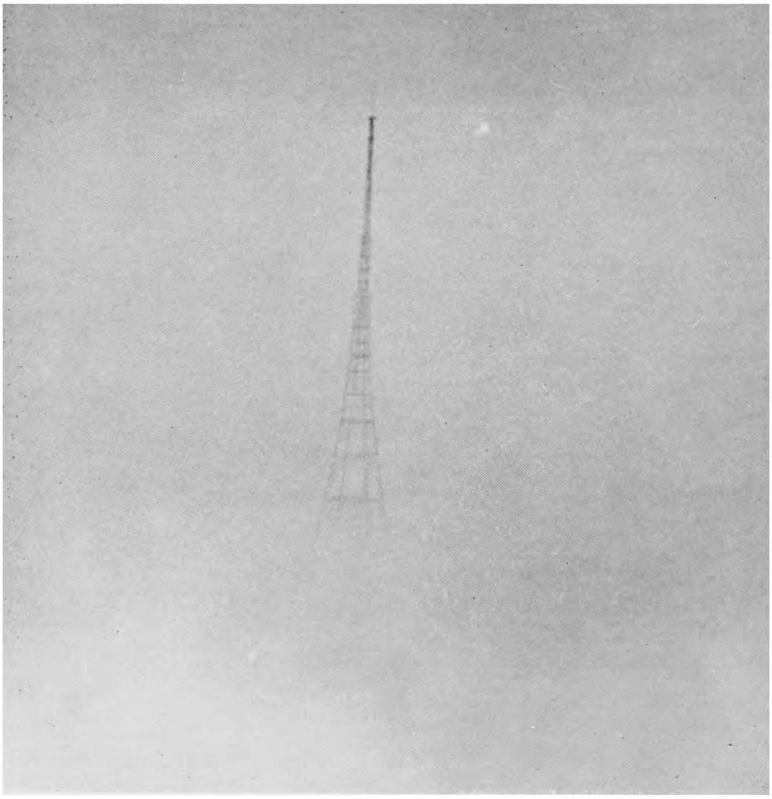
A COMPUTER PROGRAMME FOR THE CALCULATION OF MEAN RATES OF EVAPORATION USING PENMAN'S FORMULA

By C. P. YOUNG, B.Sc.
(Road Research Laboratory, Department of Scientific and Industrial Research)

Summary.—In hydrological studies estimates of rates of evaporation have to be made from meteorological data, and Penman's formula is used for this purpose at the Road Research Laboratory. A programme for a Ferranti 'Pegasus' computer has been developed by means of which rates of evaporation can be calculated rapidly from the meteorological data. Taking into account the time taken to punch the data on paper tapes, an individual rate of evaporation can be calculated in half a minute.

Introduction.—As part of the programme of research into the design of drainage structures for motorways, investigations are being made of the rates of flow in the longitudinal drains of the carriageways and in the culverts beneath the motorways that provide lateral drainage for small natural catchments. Both investigations require a knowledge of rates of evaporation which are to be estimated using the formula devised by Penman.[1, 2]

THE METEOROLOGICAL RESEARCH FLIGHT BUILDING AT FARNBOROUGH



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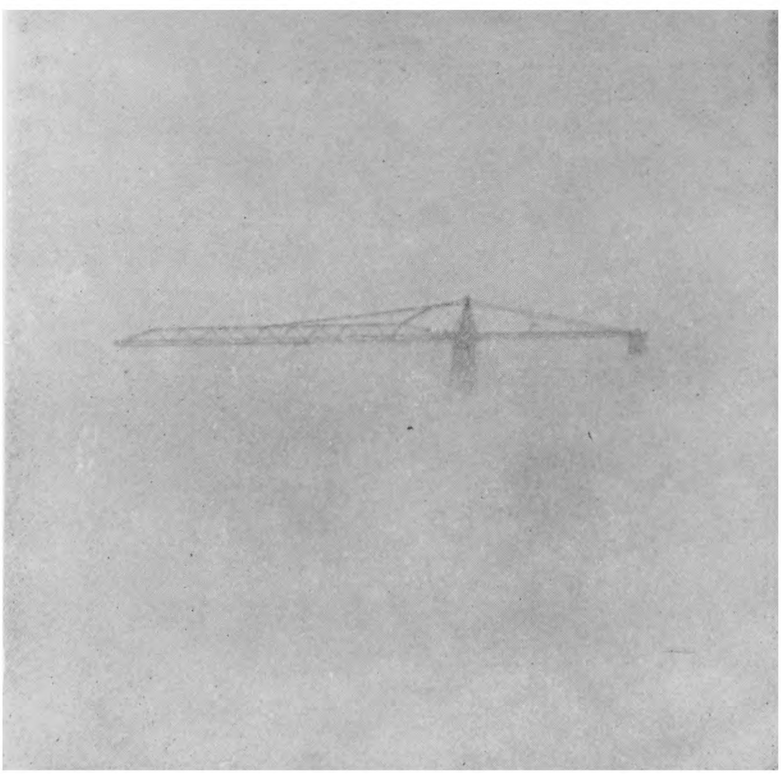

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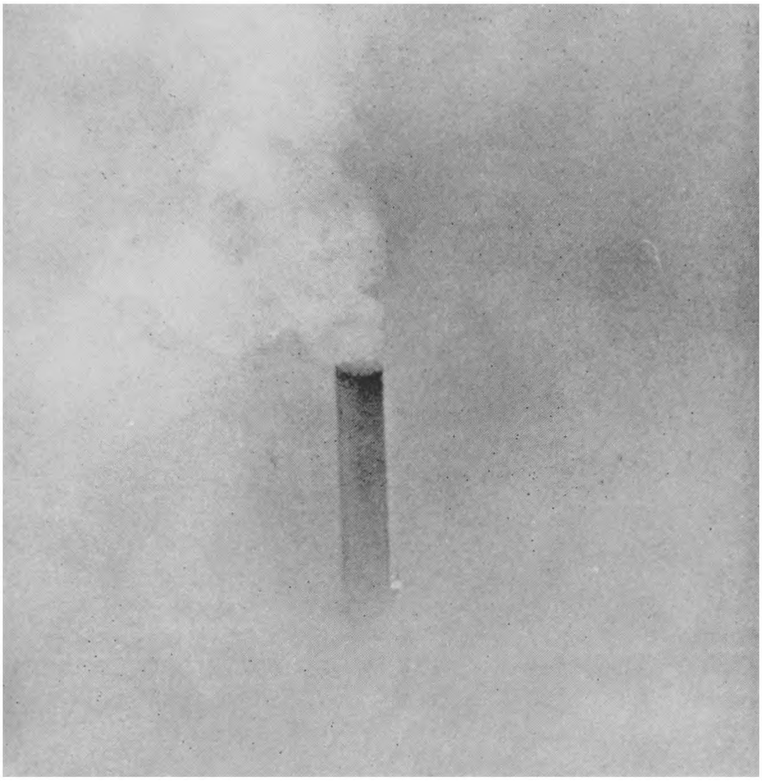

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PHOTOGRAPHS OF THE LONDON FOG, 3–7 DECEMBER 1962

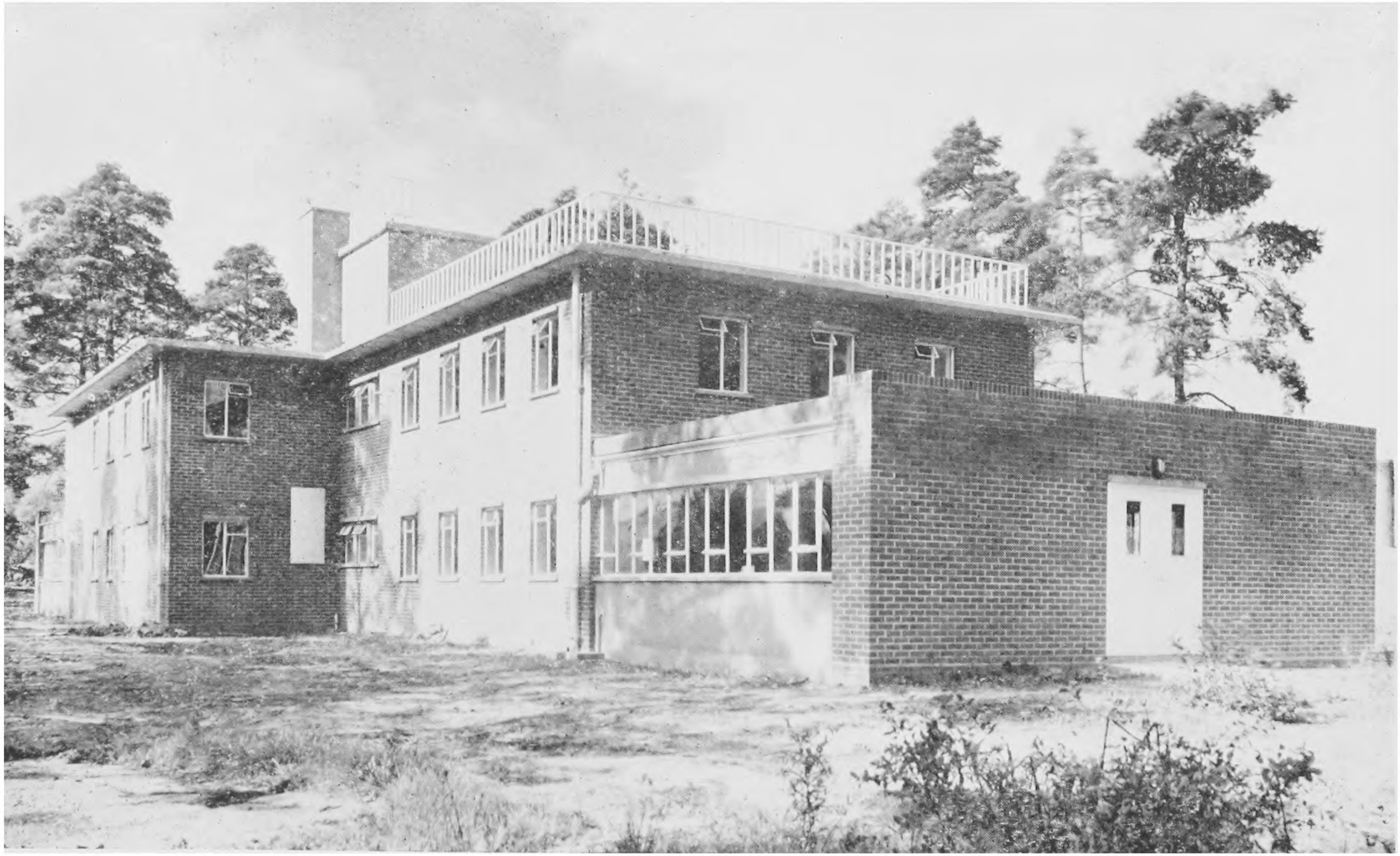
Fog developed over much of south-east England, including the London area, on the evening of Monday 3 December, gradually becoming denser on the following day with visibilities down to 10 yards or less in places, especially in the evening. There was some temporary improvement in most places on Wednesday, mainly during the day, and again on Thursday, but visibility was less than 10 yards in many places on Thursday evening. On the morning of Friday 7 December visibility improved and by evening the fog had cleared over the whole of Greater London.

The top of the fog was between 300 and 400 feet above the Thames and such places as Crystal Palace and the top of Shell building were above the fog at times. The photograph (top left) shows the television mast at Crystal Palace, while the crane (bottom left) is sited on the south bank of the Thames.

This fog period, though shorter, was in many ways similar to the bad fog of 4–9 December 1952. Visibilities in 1952 were somewhat less and the really dense fog (visibility less than 20 yd) was more widespread and persistent. The fog top of 300 to 400 feet was similar in the two cases but temperatures near the ground in low-lying areas of Greater London were about 1°C lower (night minima around minus 6°C) in the 1962 fog than in 1952. Temperatures increased rapidly with height in both cases and reached 4°C or more on hill tops near London.

Fog occurred in most parts of England during the period of London fog in 1962 but, as in the 1952 episode, it was neither as persistent nor as dense in other regions as in the London area.

To face p 85]



THE METEOROLOGICAL RESEARCH FLIGHT BUILDING AT FARNBOROUGH

Penman's formula is to be used for these investigations because it takes into account most of the physical factors involved in evaporation from natural surfaces. To reduce the effort required in the calculations, a programme has been developed for use with a Ferranti 'Pegasus' computer. The development of this programme is described.

The Penman formula.—This formula estimates E, the hypothetical rate of evaporation, as

$$E = \left(\frac{\Delta}{\gamma} H + E_a\right) \Big/ \left(\frac{\Delta}{\gamma} + 1\right) \text{ mm day}^{-1}, \qquad \ldots (1)$$

where $E_a = 0.35\,(e_a - e_d)\,(1 + \frac{u_2}{100})$ mm day^{-1}, . . . (2)

Δ = the slope of the saturation vapour pressure curve for water at a mean air temperature T_a,

γ = the constant of the wet- and dry-bulb hygrometer equation,

H = A—B, the net radiation at the earth's surface (mm day^{-1}),

A = $R_a\,(1 - r)\,(0.18 + 0.55\, n/N)$, the short-wave incoming radiation (mm day $^{-1}$), . . . (3)

B = $\sigma T_a^4\,(0.56 - 0.092\sqrt{e_d})\,(0.10 + 0.90\, n/N)$, the long-wave outgoing radiation (mm day^{-1}), . . . (4)

R_a = the theoretically calculable amount of radiation received at the earth's surface in the absence of an atmosphere, expressed in evaporation units,

r = the reflexion coefficient,

n/N = the ratio of actual to possible hours of sunshine,

σT_a^4 = the theoretical black-body radiation at a mean air temperature T_a,

e_a = the saturation vapour pressure of water at a mean air temperature T_a,

e_d = the saturation vapour pressure of water at dew-point or the actual vapour pressure at a mean air temperature T_a,

u_2 = the mean daily wind speed (mile day^{-1}) at a height of 2 metres.

If the reflexion coefficient r in equation (3) is given the value 0.25,[2] then equation (1) gives, directly, $E = E_T$, the potential rate of evapotranspiration from an extended short green crop.

Tabulation of data.—To calculate E for a given locality six basic parameters must be known. These are (i) latitude, (ii) time of year, (iii) actual hours of sunshine, (iv) the mean air temperature, (v) the mean vapour pressure and (vi) the mean daily wind speed.

Instruments are available which can measure either the net radiation received at the earth's surface, H in equation (1), or the total incoming radiation, A in equation (3). Readings from these instruments can be used to improve the accuracy of the estimate of the rate of evaporation. If measurements of H are known, some of the basic parameters need not be given. Table I shows the basic parameters needed depending upon the instruments available.

TABLE I—PARAMETERS NEEDED TO CALCULATE RATES OF EVAPORATION

	Latitude	Time of year	Radiation (Mean daily values) Incoming	Radiation Net	Sunshine hours	Air temperature	Vapour pressure or relative humidity	Wind speed
No radiation instruments	*	*			*	*	*	*
Incoming radiation readings available	*	*	*		*	*	*	*
Net radiation readings available				*		*	*	*

The three methods of using the programme are listed in Table I in order of increasing accuracy of the estimate of the rate of evaporation. When measurements of incoming radiation are available the accuracy of the estimate can be improved, but it is still necessary to know the appropriate latitude and time of year. If the net radiation is known, air temperature, vapour pressure and wind speed are the only other parameters needed to estimate the rate of evaporation.

For the purpose of the programme the units of the basic parameters are as follows:

(i) Latitude; degrees and decimals of a degree, with a negative sign for southerly latitudes.

(ii) Time of year; either as a month or as the sun's mean daily declination in degrees and decimals of a degree, with a negative sign for southerly declinations.

(iii) Radiation readings; mean daily values in calories.

(iv) Sunshine hours; mean daily values in hours.

(v) Air temperature; mean daily value either in °C or °F.

(vi) Vapour pressure; either as the mean daily value in millibars or as the mean daily relative humidity expressed as a percentage.

(vii) Wind speed; mean daily value in miles per day at a height of 2 metres.

Calculation of dependent variables.—The programme has been designed so that all the variables dependent upon the basic data are calculated directly, avoiding the use of ancillary tables and graphs. There are four dependent variables involved:

(i) R_a, the theoretical amount of radiation received at the earth's surface in the absence of an atmosphere; this is calculated from the formula:

$$R_a = \frac{1440R}{59\pi}(h \sin L \sin D + \sin h \cos L \cos D) \text{ mm day}^{-1}, \quad \ldots (5)$$

where

L = latitude,

D = sun's mean daily declination,

R = the solar constant (usually taken as 1.94 cal cm^{-2} min^{-1}) and

$$h = \cos^{-1} \tan L \tan D, \quad \ldots (6)$$

angles L and D being measured in radians.

Equation (5) neglects small effects such as the eccentricity of the earth's orbit.

(ii) N, the possible hours of sunshine; this value is found from equation (6) and is given by

$$N = \frac{24h}{\pi} \text{ hours.} \quad \ldots (7)$$

(iii) e_a, the saturation vapour pressure of water at an air temperature T_a; this is given by the formula

$$e_a = \exp \left[47.226 - \frac{6463}{(273+T_a)} - 3.927 \ln (273+T_a) \right] \text{mm of mercury} \quad (8)$$

(iv) Δ, the slope of the saturation vapour pressure curve at an air temperature T_a; this is given by differentiating equation (8), thus

$$\Delta = \frac{e_a}{(273+T_a)} \left[\frac{6463}{(273+T_a)} - 3.927 \right]. \quad \ldots (9)$$

The constants in equations (8) and (9) were determined from a multiple correlation analysis of values tabulated by Kaye and Laby[3] of the saturation vapour pressure of water between 0°C and 40°C.

The programme.—The part of the programme concerned with data input has been designed to accept data punched on paper tape in normal units without any scaling or conversion being necessary, the data being preceded by an identifying code letter. The programme has been arranged so that if any items of the basic data are constant for a series of calculations, those items need only be punched on the data tape at the start of the series. A facility for the computation of mean values from daily values is incorporated in the main computer programme. Once the data has been read by the computer, the rate of evaporation is calculated in either millimetres or inches per day.

If the reflexion coefficient r in equation (3) is given the value 0.05[1] then equation (1) gives $E = E_0$, the hypothetical rate of evaporation that would take place from an extended sheet of open water. E_0 may be multiplied by a seasonal factor f to convert E_0 to E_T, the potential rate of evapotranspiration from a short green crop. If r is given the value 0.25,[2] then equation (1) gives E_T directly. The value of r in equation (3) can be easily changed in the programme from 0.25 to 0.05 to give E_0. If r is changed to give E_0 in equation (1), the appropriate seasonal factor f should be specified. The programme will then punch out both E_0 and E_T $(= f.E_0)$.

The values of the constants in the cloudiness terms $(0.18 + 0.55n/N)$ and $(0.10 + 0.90\, n/N)$ of equations (3) and (4) can be changed, if desired, to suit local conditions.

Figure 1 shows the data as they would be punched to calculate the mean daily rate of evaporation for each month of the year and Figure 2 shows the results obtained from these data. Using the programme in its longest form, the time taken to punch the data for the calculation of 84 individual rates of evaporation was 40 minutes and the time taken for the actual calculations was 2 minutes.

```
N
UXBRIDGE  YEAR 1954                          Title copied to results tape


LAT51.5                                      Latitude constant for series


JAN TF37.9 E6.6 S2.13 W171 L          TF  mean daily air temperature °F
FEB TF37.9 E6.7 S1.74 W146 L
MAR TF44.4 E7.9 S3.34 W148 F.7 L      E   mean daily vapour pressure millibars
APR TF46.4 E7.4 S6.18 W130 F.7 L
MAY TF53.9 E10.5 S5.16 W132 F.8 L     S   mean daily sunshine hours
JUN TF58.3 E12.4 S5.41 W145 F.8 L
JUL TF58.7 E13.1 S4.91 W152 F.8 L     W   mean daily wind speed, miles per day
AUG TF60.0 E14.3 S4.91 W122 F.8 L
SEP TF57.0 E12.8 S5.67 W150 L         F   seasonal factor
OCT TF55.0 E12.7 S3.09 W170 L
NOV TF45.9 E9.5 S1.87 W151 L          L   Data complete
DEC TF44.5 E8.6 S1.72 W184 L
Z
```

FIGURE 1—SPECIMEN OF DATA AS PUNCHED ON PAPER TAPE

```
21/12/61--22                              Date and serial number of calculation
PENMAN EVAPORATION RATE PROGRAMME.        Title of Programme

UXBRIDGE  YEAR 1954                       Title copied from data tape

+0.2
+0.5
+1.3       +0.9
+2.5       +1.7
+3.1       +2.5      f.E0 millimetres per day
+3.7       +3.0
+3.6       +2.9
+2.8       +2.3
+2.2
+1.0
+0.3
+0.2   ------------->  E0 millimetres per day
```

FIGURE 2—SPECIMEN OF RESULTS CALCULATED FROM DATA SHOWN IN FIGURE 1

A detailed specification of the programme which shows the conventions to be observed in punching the data and in altering the constants, is available at the Road Research Laboratory.

Acknowledgments.—The author wishes to thank Dr. H. L. Penman for useful comments and suggestions on the preliminary proposals and specification of this programme.

The computer programme described in this article was prepared as part of the programme of the Road Research Board of the Department of Scientific and Industrial Research. The article is published by permission of the Director of Road Research.

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AN OSCILLATORY PRESSURE JUMP AT MALTA

By T. H. KIRK

Examples have already been given[1] of pressure jumps at Malta. Most of them have been characterized by oscillations in the wind and pressure records after the initial sharp rise of pressure. A particularly good example of an oscillatory pressure jump occurred just after 0100 local time (GMT + 1 hr) on 6 September 1960 (Figures 1 and 2). The marked periodicity in the wind speed trace was particularly evident, even when the periodicity in the direction trace had largely disappeared.

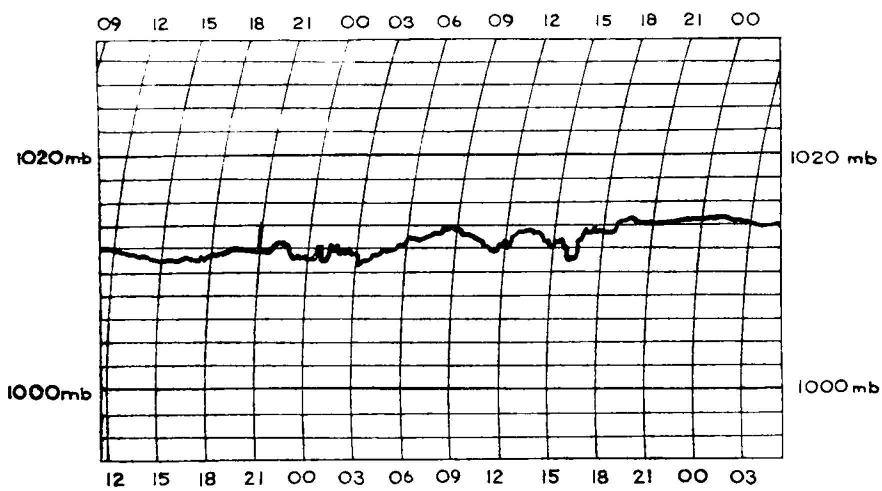

FIGURE 1—BAROGRAM FOR LUQA, MALTA, 6 SEPTEMBER 1960

Goldie[2] has dealt with the effects at the surface attributable to waves at an approximately horizontal surface of discontinuity in the atmosphere, and it may be of interest to quote his remarks when deriving the variation vector (δU) of the surface wind:

"It is a matter of much interest that, even in cases where the surface wind may have dropped to calm at night, this δU effect is strikingly evident in the form of a little breeze rising steadily to a maximum and then dying out in the same way at the appropriate times."

The wind record can be interpreted in much the same way, for after 0300 local time the surface wind was very light and yet the periodicity remained particularly evident in the speed. The 0001 GMT Qrendi ascent shows that the height of the inversion was at approximately 350 feet above station level at Luqa. The 1200 GMT ascent shows that the inversion had increased in height by 30 mb, i.e. approximately 900 feet, so that if we could assume that the whole of this increase took place at the pressure jump we should have a height of about 1250 feet for the inversion at Luqa.

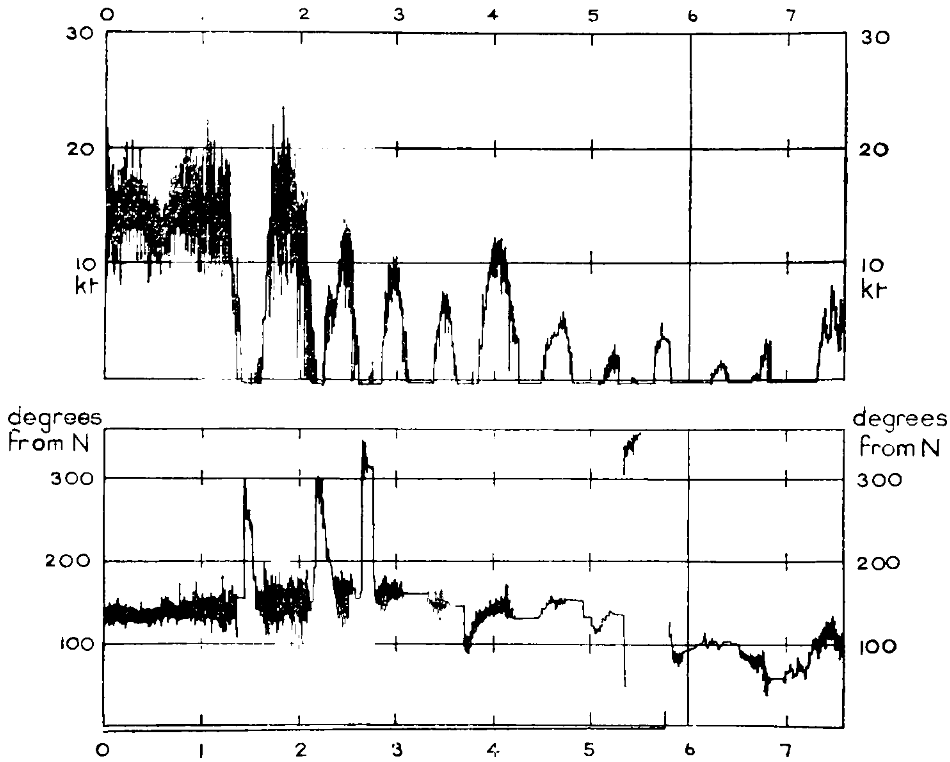

FIGURE 2—ANEMOGRAM FOR LUQA, MALTA, 6 SEPTEMBER 1960

Figure 3 shows the synoptic situation at the surface at 0001 GMT, a discontinuity line being drawn along the trough. If we take the orientation of this line as 030–210° at Malta then we should expect the pressure jump to arrive from the direction (210+90)°, i.e. from 300° approximately. At the onset of the sharp pressure rise there would be no geostrophic equilibrium and the surface wind would blow at right-angles to the pressure jump line, i.e. from approximately 300°. This is in accordance with the first three swings of the wind direction. After 0300 local time, if the direction of the waves be taken at right-angles to the trough line, the observations are consistent with a mean wind (U) of approximately 5 knots from 140–150° and a variable vector (δU) of 5 knots. The surface wind would then be varying between 140° and 150° 10 knots and zero as the observations confirm.

Using the value of δU in the formulae given by Goldie, we obtain 10 knots for v, the speed of the waves relative to the component of the surface wind in the direction of the waves. The wind is out of phase with the pressure variations for we note that the first sharp decrease of wind is due to the pressure jump.

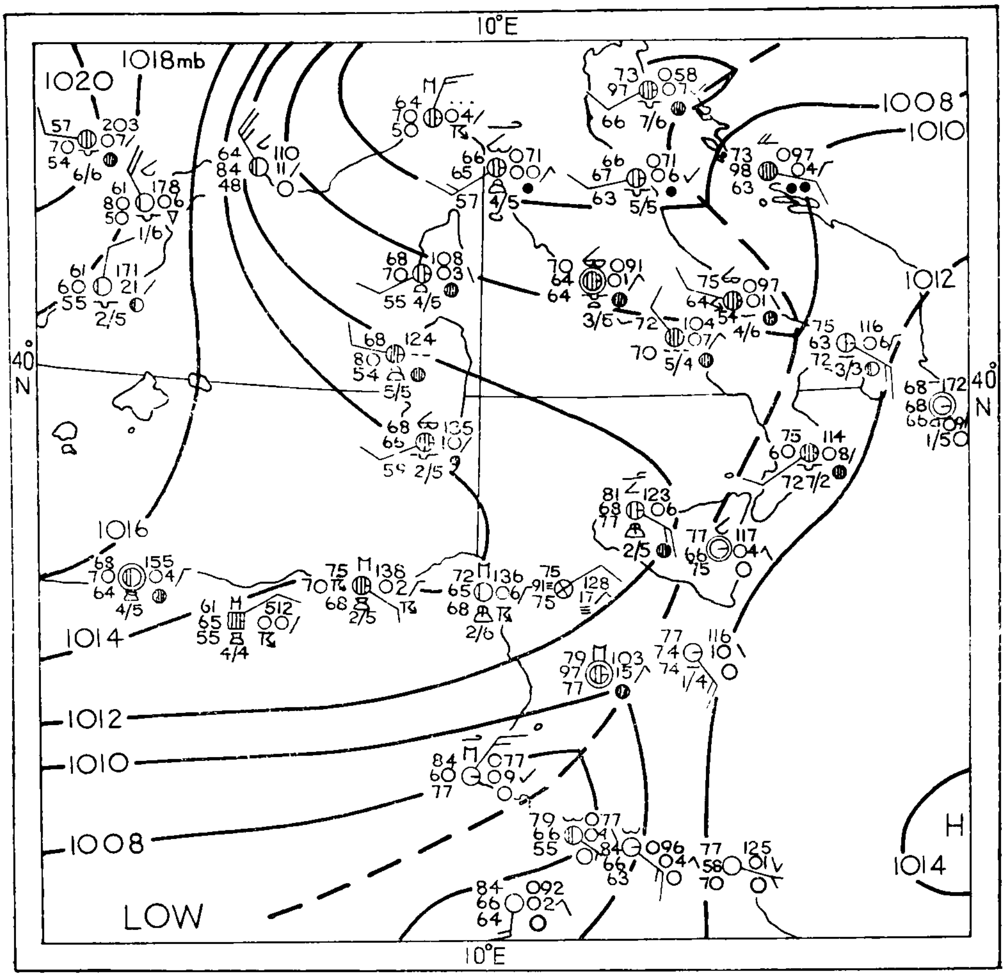

FIGURE 3—SURFACE CHART FOR 0001 GMT, 6 SEPTEMBER 1960

We have, therefore, in Goldie's notation

$$U \cos \alpha - V = +10 \text{ knots}$$
$$U \cos \alpha = 5 \text{ knots approximately}$$
$$\text{therefore } V = -5 \text{ knots}$$

i.e. the waves are from the north-west at a speed of about 5 knots.

The period of the waves shown by the anemogram is about 40 minutes. Using this fact we derive 120 metres for the wavelength. The amplitude of the waves comes to somewhere between 200 feet and 600 feet depending on the assumed height of the inversion. These simple computations have of course only limited application because the surface wind is not entirely representative of the layer of air below the inversion.

It is of interest to note that Tepper[3] has referred to oscillatory pressure jumps and has cited experimental evidence that hydraulic jumps are oscillatory when $h_2/h_1 < 2$, h_1 and h_2 being the heights of the bottom layer before and after the jump. Owing to the uncertainty in the height of the inversion immediately after the pressure jump it is difficult to know whether or not this criterion was satisfied in this instance. However, even assuming that the 1200 GMT value of the inversion height was applicable at the jump, we have, reckoning from sea level,

$$\frac{h_2}{h_1} = \frac{1550}{650} = 2.4 .$$

Experience in the Mediterranean does undoubtedly support the idea that weak pressure jumps are oscillatory.

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551.509.317:551.509.326

A MODIFIED INSTABILITY INDEX

By G. J. JEFFERSON, M.Sc.

The instability index for the months May to August in the British Isles and near continental areas described by Rackliff[1] possesses the very desirable features for a forecasting tool of simplicity and quick computation. Some attempt has been made at London (Heathrow) Airport to use it in midsummer, especially in regard to air-mass thunderstorm activity, and to ascertain the possibility of its application to wider areas. While no comprehensive investigation of its value has so far been possible, one or two features have come to light which suggest that some modification is necessary for it to be used in this way.

On one occasion the instability index (ΔT), for an area covering all radiosonde stations of the North Atlantic from Bermuda to Greenland, the British Isles and the eastern half of Canada and the United States of America, was highest (34) at Ocean Weather Station "A" (62°N 33°W), in an area of ocean where thunderstorms are almost unknown, while in a thundery area south-west of New York the index was about 29. A number of trials have also been made over the Europe–Mediterranean area. One example of this is given in Figure 1. It will be noted that this chart is based on the ascents for 1200 GMT in place of the midnight ascents used by Rackliff, and would be expected to show a closer coincidence to actual thunderstorm occurrence since the effects of advection are reduced. Isopleths of ΔT show areas of maximum over Spain, northern Italy to Yugoslavia with a northward extension towards north-west Germany and other areas near western Ireland and over Scandinavia. Also on Figure 1 are plots of rain, showers and thunderstorms for 1500 GMT on the same day. These show that the southern areas of maximum ΔT coincided fairly well with the areas where thunderstorms occurred but that nothing heavier than showers was reported from the northern area of maximum. SFLOC reports for 1500 and 1600 GMT covered fairly wide areas of continental Europe south of 50°N but there were no reports north of 50°N. These facts suggest that there will be a higher threshold value for thunder in cold than in warm air and that some modification is necessary to the method of evaluation if the index is to be used over greater ranges of temperature (or latitude) than those for which it was evolved, or indeed if it is to be used at other seasons in north-west Europe.

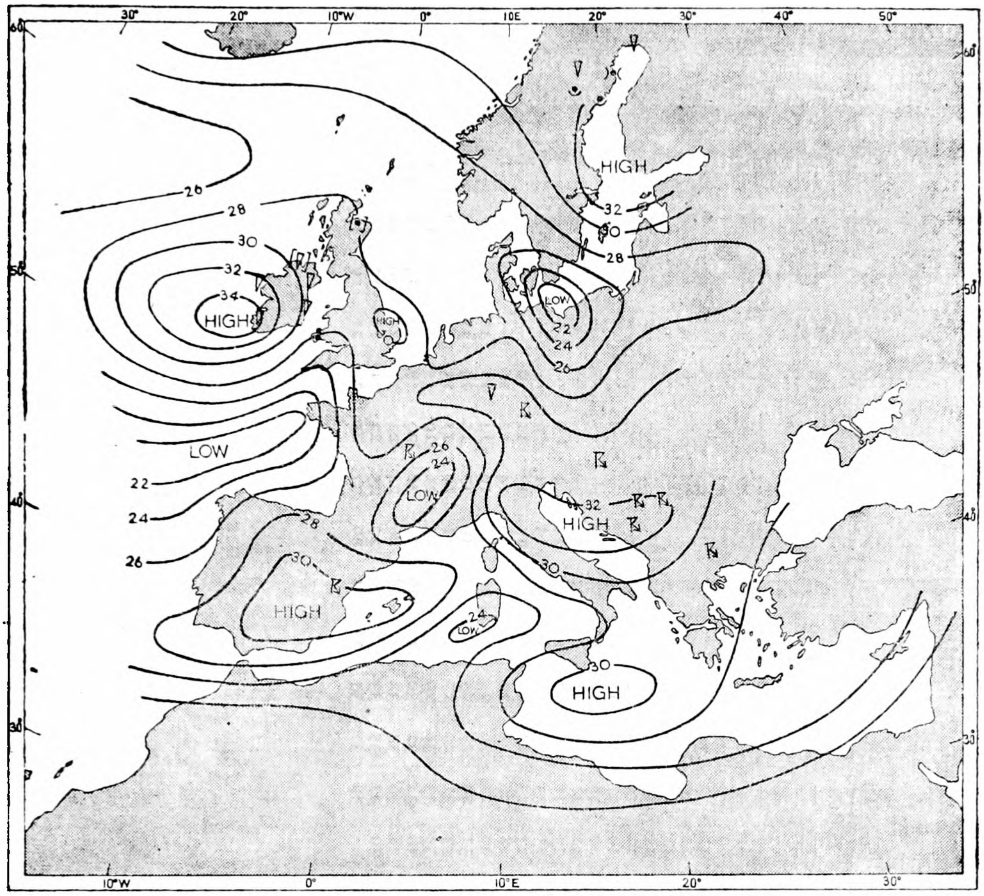

FIGURE I—ISOPLETHS OF INSTABILITY INDEX (ΔT) AFTER RACKLIFF FOR 1200 GMT, 18 JUNE 1962

Present weather plots at 1500 GMT. Plots of weather in past hour are in square brackets.

The instability index ΔT is a number of only relative significance, and, unlike the index of Showalter,[2] its magnitude will in fact depend not only on the stability but also on temperature. This is readily apparent if saturated air with a lapse rate equal to the saturated adiabatic between 900 and 500 mb (that is, constant wet-bulb potential temperatures, θ_w) is considered. The following table shows how ΔT varies with θ_w in this case.

TABLE I—RELATIONSHIP BETWEEN ΔT AND θ_w

θ_w°C	T_{500}°C	ΔT
0	—41	41
5	—33	38
10	—26	36
15	—17	32
20	— 9	29
25	— 1	26

It can be seen that as θ_w rises, the instability index for air of neutral stability falls steadily. Values of θ_w between 10°C and 20°C would be fairly typical of air over north-west Europe in the summer months which was used by Rackliff to evaluate the threshold value of ΔT to give thunderstorms. The corresponding variation of ΔT in Table I is between 36 and 29. Since actual soundings resembling the air used to evaluate Table I are of the type usually associated

TABLE II—VALUES OF T_J DERIVED FROM θ_{w900} AND T_{500}

	T_{500} (°C)																														
θ_{w900}	−40	−38	−36	−34	−32	−30	−28	−26	−24	−22	−20	−18	−16	−14	−12	−10	−8	−6	−4	−2	0	2	4	6	8	10	12	14	16	18	20
	T_J (°C)																														
0	29	27	25	23	21	19	17	15	13	11	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1	31	29	27	25	23	21	19	17	15	13	11	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2	32	20	28	26	24	22	20	18	16	14	12	10	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
3	34	32	30	28	26	24	22	20	18	16	14	12	10	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
4	35	33	31	29	27	25	23	21	19	17	15	13	11	9	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
5	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
6	—	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
7	—	38	36	34	32	30	28	26	24	22	20	18	16	14	12	10	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
8	—	—	38	36	34	32	30	28	26	24	22	20	18	16	14	12	10	—	—	—	—	—	—	—	—	—	—	—	—	—	—
9	—	—	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	—	—	—	—	—	—	—	—	—	—	—	—	—
10	—	—	—	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	—	—	—	—	—	—	—	—	—	—	—	—
11	—	—	—	—	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	—	—	—	—	—	—	—	—	—	—	—
12	—	—	—	—	—	38	36	34	32	30	28	26	24	22	20	18	16	14	12	10	—	—	—	—	—	—	—	—	—	—	—
13	—	—	—	—	—	—	38	36	34	32	30	28	26	24	22	20	18	16	14	12	10	—	—	—	—	—	—	—	—	—	—
14	—	—	—	—	—	—	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	—	—	—	—	—	—	—	—	—
15	—	—	—	—	—	—	—	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	—	—	—	—	—	—	—	—
16	—	—	—	—	—	—	—	—	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	—	—	—	—	—	—	—
17	—	—	—	—	—	—	—	—	—	38	36	34	32	30	28	26	24	22	20	18	16	14	12	10	—	—	—	—	—	—	—
18	—	—	—	—	—	—	—	—	—	—	38	36	34	32	30	28	26	24	22	20	18	16	14	12	10	—	—	—	—	—	—
19	—	—	—	—	—	—	—	—	—	—	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	—	—	—	—	—
20	—	—	—	—	—	—	—	—	—	—	—	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	—	—	—	—
21	—	—	—	—	—	—	—	—	—	—	—	—	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	—	—	—
22	—	—	—	—	—	—	—	—	—	—	—	—	—	38	36	34	32	30	28	26	24	22	20	18	16	14	12	10	—	—	—
23	—	—	—	—	—	—	—	—	—	—	—	—	—	—	38	36	34	32	30	28	26	24	22	20	18	16	14	12	10	—	—
24	—	—	—	—	—	—	—	—	—	—	—	—	—	—	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	—
25	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9

with convectional activity, the threshold value of $\Delta T = 30$ for thunderstorms given by Rackliff can be seen to be reasonable. Table I shows that ΔT would have a value of 30 when $\theta_w \simeq 18°C$. Also the change of ΔT with θ_w is approximately linear and it is suggested that the following amended formula based on the data in Table I will give a value of the instability index which is independent of temperature and which will still give the same threshold value for thunderstorms over a wide range of temperature:

$$T_J = 1.6\ \theta_{w900} - T_{500} - 11$$

where T_J = the amended thunderstorm index, θ_{w900} = 900 mb wet-bulb potential temperature and T_{500} = dry-bulb temperature at 500 mb. With saturated air of neutral stability this gives a value of $T_J = 30$ when $\theta_w = 18°C$, a typical value for summer thunderstorm conditions over the British Isles. Figure 2 shows isopleths of T_J for the same occasion as Figure 1 and it is evident that the northern maximum is now much less prominent.

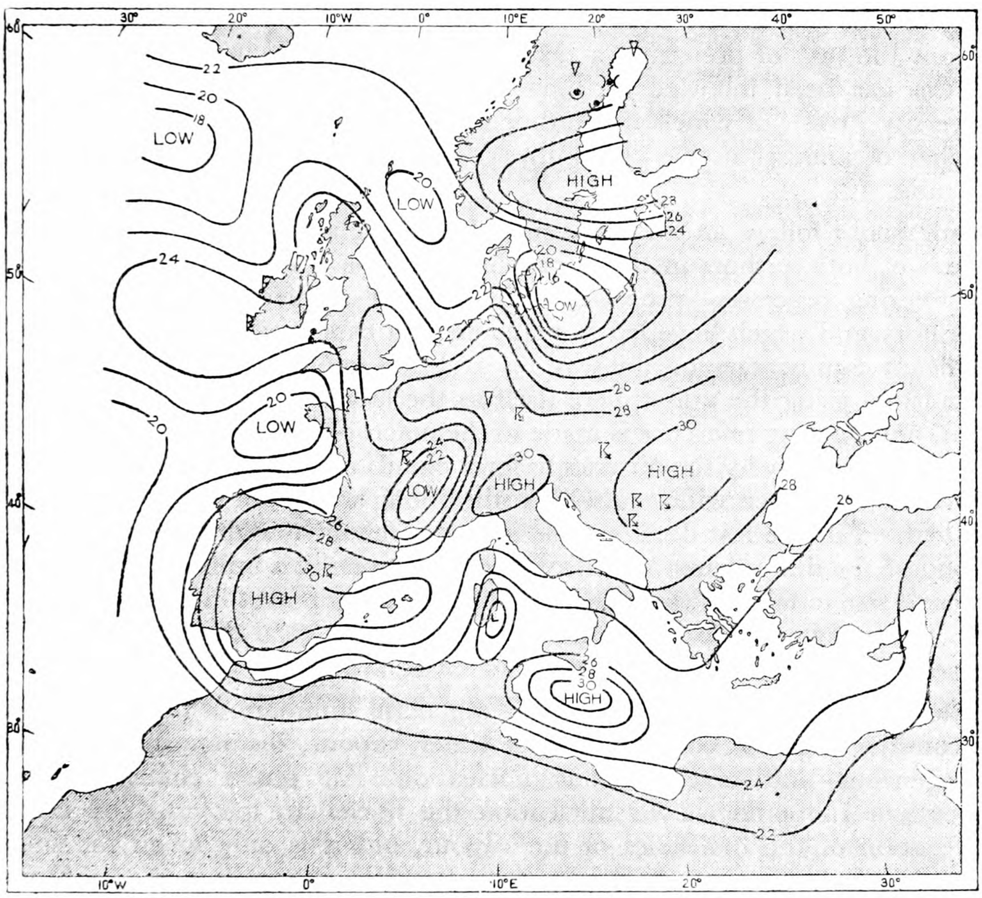

FIGURE 2—ISOPLETHS OF MODIFIED INSTABILITY INDEX (T_J) 1200 GMT, 18 JUNE 1962

Present weather plots at 1500 GMT. Plots of weather in past hour are in square brackets.

By the introduction of this altered formula some of the speed of evaluation is lost. Table II is therefore intended to overcome this. It shows values of T_J

for ranges of θ_{w900} and T_{500} which would cover most normal requirements and can be used to evaluate the modified instability index as quickly as in the original case.

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551.574.1(048.1)

THE PHYSICS OF RAINCLOUDS

By R. F. JONES, B.A.

The deceptively simple question of "how does it rain?" has led the meteorologist interested in the physics of clouds into increasingly complicated fields of study, the difficulties and range of which have been recently recognized by the creation of a professorship in cloud physics at Imperial College, University of London. The first holder of this chair, Professor B. J. Mason, was the first to attempt the task of preparing a textbook on this advancing subject in 1957[1] and this has been followed in 1962 by a further textbook* (from the rival University Press), of which the author is Dr. N. H. Fletcher, until recently a member of another active cloud-physics group led by Dr. E. G. Bowen in Australia.

Both books follow an almost identical approach which reflects the prime interest of both authors in the microphysics of the condensation, sublimation and freezing processes—processes which can be studied individually in the laboratory and which have led to many elegant experiments. It is, however, a significant commentary on the way research has gone, and a reflexion of the difficulty of using the atmosphere itself as the laboratory, that, again in both books, only passing reference is made to the macrophysics or dynamics of cloud systems, how and why the air rises to form clouds and how quickly, so that the question "how much will it rain?" is still a long way from solution. What we *have* learned in the last decade or so is how a few favoured droplets among a myriad of cloud droplets—on the average about one in a million—can grow to sufficient size to fall to the ground as rain. The story makes interesting reading and we can follow in brief outline Dr. Fletcher's logical development of the theme.

After a brief chapter, which is really a general summary of the whole book, we consider first the condensation of water vapour, distinguishing between homogeneous and heterogeneous nucleation. All phase changes require nucleation. In homogeneous nucleation the nuclei are provided by chance aggregation of the molecules of the vapour, and it is only when the supersaturation is large that such aggregates last long enough and are formed sufficiently frequently to have a chance of further growth into droplets. In heterogeneous nucleation, condensation gets off to a good start by using particles of foreign material as a framework to which molecules of the vapour can attach themselves, so that the embryo droplet is more readily formed at a much lower supersaturation. Because the atmosphere always contains airborne

* *The physics of rainclouds*, by N. H. Fletcher. 9in. x 5¾in., pp. x + 386, *illus.*, London, Cambridge University Press, Bentley House, 200 Euston Road, London, N.W.1, 1962. Price: 65s.

foreign particles, the process of heterogeneous nucleation is the atmospheric condensation process and water-vapour supersaturation never becomes large. The theory of nucleation is complex but Dr. Fletcher's chapter takes us carefully through from homogeneous nucleation to nucleation by ions and to nucleation by insoluble and soluble particles, with the effects of the structure of the particles. By the end of the chapter we are convinced that the particles that really matter in atmospheric condensation processes are relatively large and preferably soluble, and that homogeneous nucleation of the liquid phase and condensation on ions have no part to play in nature. What we mean by "relatively large" in this context becomes clearer in the next chapter when the naturally occurring nuclei are considered.

An enormous amount of observational work has gone into the collection of nuclei of all the sizes which occur in the atmosphere. Many of the determinations have relied on an expansion chamber, a method which produces high supersaturation not typical of the free atmosphere, so that many of the nucleus counts have no relevance to cloud physics but are really measures of the total nucleus concentration. This total concentration is enormously variable, the average per cubic centimetre ranging from about 1000 in air near the tops of high mountains and over the oceans to about 100,000 in city air, but only the larger hundred or two hundred of these take any part in condensation processes and measurements have shown these to have radii of 0.1μ or greater. These are referred to as "large" nuclei while "giant" nuclei, which are composed mostly of sea-salt, have radii greater than 1μ. Much is made here, and later in the book, of the difference between continental and maritime clouds which is traced to a basic difference in nuclei; the continental air has more of the efficient "large" condensation nuclei than maritime air and therefore a greater concentration of droplets when cloud is formed.

Having decided which nuclei are important in the formation of cloud, the author next considers the cloud droplets themselves, which are formed on the nuclei, and the methods used to determine droplet concentrations and size-distributions together with their integrated effect (total liquid-water concentrations) in cloud. The general shape of droplet distribution curves, when number concentration is plotted against drop radius, is bell-shaped but generally asymmetrical with a tail extending towards large radii. Clouds which show no tendency to develop rain have a narrow spread of droplet sizes while the clouds which ultimately give rain have a large spread. This is claimed as a distinguishing feature between cumulus clouds found in continental air and those found in maritime air, the former with a narrow droplet spectrum showing less tendency to rain for a given cloud thickness than the latter which have a wider spectrum. How difficult it is to get a broad spectrum of droplet sizes by condensation alone is shown by the theoretical calculations of the next chapter from which it is learned that, because in the initial stages of condensation the smaller particles grow much more rapidly than the larger, condensation alone leads to a narrowing of the drop-size spectrum.

One of the processes which might widen the size spectrum of droplets is coalescence between droplets and this is next considered. Coalescence between droplets having radii less than 18μ has been shown both theoretically and in practice to be unlikely, but larger droplets can sweep up the droplets in their path as they fall with an efficiency which increases as their size increases. This process can be used to explain the fact that rain falls on occasions from non-freezing clouds and the theoretical arguments, using somewhat idealized conditions, support this conclusion by showing that the times of growth of droplets to raindrop size are reasonable. It is an interesting demonstration of the development of ideas of rain-producing mechanisms, even in the last 15 years, to find this chapter commence "The fact that rain can fall from clouds whose temperatures are everywhere warmer than freezing is now sufficiently well known to require no documentation", but the reference to radar, which has contributed notably in providing evidence for this assertion, is disappointingly perfunctory.

The other powerful mechanism leading to the formation of rain, and probably the only one in extensive clouds where up-currents are gentle, involves the ice-phase and is usually known as the Bergeron process. This basic theory relies on the fact that the saturation vapour pressure over ice is less than that over supercooled water at the same temperature. An ice crystal in the presence of supercooled water droplets is therefore in an environment which is supersaturated and grows rapidly while the droplets evaporate in the endeavour to maintain saturation with respect to water. If the ice crystals are relatively few they will grow quite large and will acquire a fall-speed large compared with that of the droplets, so that they will also grow by accretion of droplets as they fall, finally melting to raindrops as they descend below the melting level. All this has been known in outline for some time, but, as Dr. Fletcher shows, the details of the production of the original ice crystals are still obscure. Ice crystals do not form at all readily in the atmosphere at temperatures higher than about —15°C, either by the freezing of droplets or by direct sublimation, and, without the presence of suitable nuclei, would probably not form at all until temperatures fell below about —40°C (homogeneous nucleation). The theories of homogeneous and heterogeneous nucleation of ice from the water or vapour phase are similar in principle to those of nucleation of water from the vapour phase, but the surface structure of the nucleus assumes a greater importance. Experiments show that, if a given volume of air is cooled, more and more nuclei become active as freezing nuclei but little is known about the chemical composition and origin of these particles except that they are probably solid and insoluble. Laboratory experiments with different mineral dusts have given a variety of threshold temperatures and it is thought that most naturally occurring freezing-nuclei originate at the earth's surface. The book contains a carefully reasoned discussion of Bowen's meteor-dust hypothesis resulting in a verdict of "non-proven". A few substances, which do not occur naturally in any quantity, have a crystal structure so similar to ice that they might be expected to be efficient as ice-forming nuclei. This has in fact been shown to be true and the most efficient of these, which can produce a few ice crystals at temperatures as high as —4°C and vastly more as temperatures decrease, is silver iodide. Following the discovery of a simple way of dispensing silver iodide in finely divided form, as a smoke from a burner, this substance has achieved notoriety from its use in attempts to increase rainfall. This and other methods of modifying clouds are discussed realistically in the last three chapters of the book. No support is given to exaggerated claims, and the great difficulties of verification of any effect are stressed. It is here that the lack of knowledge of the dynamics of cloud systems is most felt; for if we cannot say how much it will rain naturally in a given situation, how can we say whether an increase in rainfall has been achieved?

The book is clearly written and well produced with a few minor errors only and, although the advances it has to report since Mason's book was written are few and the general approach is similar, there is always room among text-books for one of this quality.

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REVIEW

Microcards of IGY meteorological data, by G. London. 9½ in. × 6¼ in., pp. x + 78, *illus.*, World Meteorological Organization, Geneva, 1962. Price: Sw. fr. 7.—.

The present virtual completion of the task of reproducing meteorological data of the International Geophysical Year (IGY) on microcard affords an opportune time for this report by Dr. G. London, Chief of the IGY Meteorological Data Centre of the WMO Secretariat, to place on record some of the problems of collection, cataloguing, storage and publication difficulties inevitably encountered with some seven million synoptic surface and upper air observations.

It is emphasized in the introductory remarks that the main underlying principle which determined the basic arrangement of the microcards was the fact that such unique records should be prepared and devised in such a way that any of the observations could be traced quickly and easily. Naturally the procedures chosen were determined to some extent by the characteristics of the material collected, and the first chapter gives a brief description of the WMO standard forms that were used and compiled by the participating meteorological services.

With such an unprecedented programme of scientific observations, a careful registering of incoming forms was imperative, and Chapter II concisely shows that the system should constitute a complete, reliable and permanent record of information which, even after the termination of the IGY, could still be used to trace and retrieve the original observations.

After a small section considering the complementary problem of storage, the final chapter is devoted to the major difficulties concerning the actual publication of the data.

In more detail it is shown that a complete set of microcards for the IGY period was made to consist of four parts corresponding to the WMO standard forms, the basic layout being in terms of (i) type of observation (ii) geographical region and (iii) chronological period.

Here again we see that the report considers the danger in the use of unconnected classifying principles which in themselves would defeat their own purpose. Only by a system that was based on a classification scheme embodying the characteristics of the material itself, could the data be readily accessible, each microcard being identifiable by a combination of two groups of three numerals indicating type of form and synoptic hour with the appropriate pentad code.

The volume is concluded by the inference that individual microcard reference numbers constitute, at the same time, a classification system for the whole of the synoptic meteorological data published on microcards and will serve as guides for filing and information retrieval. It is significant that the system was adaptable enough for the International Geophysical Co-operation reports (1959) to be grouped and coded by the same principles of layout and notation.

The information supplied will be of considerable interest to the users of microcards and the principles formulated will, no doubt, find a use in any future projects of a similar nature.

J. F. DIXON

OBITUARY

Mr. D. H. Clarke.—It is with great regret that we record the sudden death on 14 January, 1963, at the age of 60, only seven months following his retirement, of Mr. D. H. Clarke, Senior Experimental Officer. It was on 17 December 1926, that Duggie joined the Meteorological Office at Aldergrove as a Temporary Clerk, having had previous experience in meteorological work while serving in the Royal Air Force in Iraq. He remained at Aldergrove until the early 1930's when moves entailed service at Croydon, Headquarters, Birmingham and Dunstable. From early 1940 and throughout the war years he was in charge of the training of W.R.A.F. Meteorologists in London and at Stonehouse. In 1948 he returned to Dunstable on appointment in charge of the Administrative Branch and occupied this post until his retirement in June 1962.

Duggie had a great charm of manner and his many friends both in the Meteorological Office, Works Services Officers with whom he had many contacts while at Dunstable and also his numerous local friends, will feel regret that he did not live longer to enjoy retirement. Among the outside interests in which he took an active part was membership of the South Bedfordshire Preservation Society and the Manshead Archaeological Society. He was keen on outdoor life and the country while indoor hobbies included woodwork at which he was most efficient and artistic.

To his widow and son, now employed by Shell Mex in the Persian Gulf as a Geologist, his friends and colleagues offer deepest sympathy in their sad loss.

A.A.V.B.

METEOROLOGICAL OFFICE NEWS

The Meteorological Office Football Club (Bracknell) having received a bye in the first round, safely entered the third round of the Lewis Cup when they beat Cheltenham Civil Service A.F.C. by 7 goals to 3 on 28 November. Although a goal down inside two minutes, the team fought back to be 3 - 1 in the lead at half-time and were worthy winners of a good, exciting game. The goalscorers were Archard, Underwood 3, Johnson 2, own goal 1 and the team was Robinson (Heathrow); Crisford (White Waltham), Saunders (M.O. 5c); Hanson (M.O. 18), Rattray (M.O. 3), Green (M.O. 10); Morgan (M.O. 18), Underwood (M.O. 5c), Johnson (Heathrow), Ashby (M.O. 15) and Archard (M.O. 3). The Club is grateful to the Director-General of the Meteorological Office for agreeing to have the teams presented to him before the kick-off and to the many other members of the staff who supported the team. The team will now be meeting Portsmouth Civil Service A.F.C. for the right to enter the last eight in the competition.

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RELATIONSHIPS BETWEEN SEA-LEVEL ISOBARS AND THE WIND SPEED AT 900 METRES

By C. J. BOYDEN

Introduction.—In forecasting the wind speed just above the earth's friction layer it is customary to apply the geostrophic relationship to the sea-level isobars and then make a rough adjustment for the cyclostrophic term if the flow has pronounced curvature; precise measurement is difficult because the cyclostrophic term involves the curvature of the trajectory, not of the isobars. Allowance can also be made for the lag of the wind behind the equilibrium speed during acceleration and deceleration. Deviations from balanced flow are usually accounted for in these ways when they are observed, but in forecasting a wind speed they are largely disregarded because the major problem, as well as the main source of error, is the forecasting of the pressure gradient. Nevertheless, it was thought to be of interest to make an assessment of the lag of the wind, both in magnitude and time, when the pressure gradient is changing. In the course of this work it was found that the gradient wind speed, based on isobaric curvature, was very different from the true wind, and empirical relationships were found which should be useful to the forecaster. All conclusions were based on wind speeds measured by the Crawley radar at a height of 900 m (a standard level in the reports) as compared with geostrophic and gradient winds measured over south-east England on hourly charts drawn in the Central Forecasting Office. Only the winter months October to March were studied.

The main causes of differences between reported 900 m wind speeds and gradient wind speeds are the following:

(i) Both the wind and the isobaric pattern are subject to small-scale variations. The radar wind speed is a measurement over two or three minutes; this may not be representative of the speed over a longer period and may not therefore match the pressure pattern on the synoptic scale.

(ii) The wind varies between 900 m and sea level. Since the average wind increase with height between 850 mb and 700 mb is about 2 kt/km, it seems reasonable to assume about 2 kt as the average geostrophic difference between 900 m and sea level.

(iii) The geostrophic scale used was based on an air temperature of 10°C. This introduced an average error of about four per cent and this was regarded as cancelling (ii), above.

(iv) Inaccuracies in the isobars are inevitable, partly through inaccurate drawing to the observations and partly because of pressure errors. These inaccuracies should be small over south-east England, since observations there are comparatively plentiful.

(v) There may be radar wind errors, either random or systematic. Evidence is given for a systematic error.

(vi) All gradient winds used in the comparisons were based on isobaric curvature, although some estimates are given of the mean errors involved.

(vii) There is a lag in the adjustment of the wind to a changing pressure gradient. This adjustment may become necessary through a change of pressure gradient with time or because air moves through the pattern to a place where the gradient is stronger or weaker.

Ideally an investigation of this kind would be made following the movement of a parcel of air. This is impossible with a normal observational network unless assumptions are made about the ageostrophic flow which is the subject of the investigation. The local change of pressure gradient in the Crawley area over a 3-hour period was therefore taken as a measure of the change undergone by a parcel of moving air. Thus acceleration was defined by a local increase of pressure gradient (measurement being made along about 200 miles of isobar), and the acceleration of the moving air was regarded as equal to the local increase of geostrophic wind speed during the period. Over periods of three or even five hours the approximation was regarded as satisfactory on most occasions and for most purposes because of the small variations of pressure gradient and curvature usually found at any instant along such a short trajectory. Only when the isobars had pronounced curvature and were changing direction with time did it seem that this relationship required substantial modification. In order to verify this a check was made using the 73 occasions of tightening cyclonic isobars on which Table II was based. The pressure gradient was measured at Crawley and then on the chart of three hours before at a point 130 miles upwind from Crawley. This distance was the average 3-hour travel of the air, and the trajectory was taken along the isobars of the later of the two charts. On the majority of occasions there was an increase of geostrophic wind on the air as it moved to Crawley. The average increase was about a quarter of the initial speed, whereas the local increase of geostrophic wind at Crawley over the three hours was about a third. The difference is accounted for mainly by some bias in selection (see below) and to a small extent by the cross-isobar flow, whereby the air moved from a region of higher pressure and normally weaker gradient than was assumed. It therefore appeared that for most isobaric curvatures the local change over three hours adequately represented the change in speed of the moving air. This relationship doubtless depends on the fact that the air moves only slowly through medium-scale features of the pressure pattern, and it may not hold at high levels in the atmosphere.

Radar wind errors.—In order to assess the accuracy of radar wind speeds at 900 m a comparison was made with geostrophic wind speeds on occasions when the isobars were straight and the wind was steady. The criterion for steadiness was that the geostrophic wind, measured to the nearest five knots, was within five knots of the geostrophic speed at the same place three hours earlier. The period October to March in each of the winters 1959–60, 1960–61 and 1961–62 yielded a total of 174 pairs of values. Figure 1 shows the relationship between the geostrophic wind speed and the average excess over the 900 m wind speed from Crawley. The scatter of the points is fairly large, partly because of the inevitable bias in measuring a wind to the nearest 5 knots.

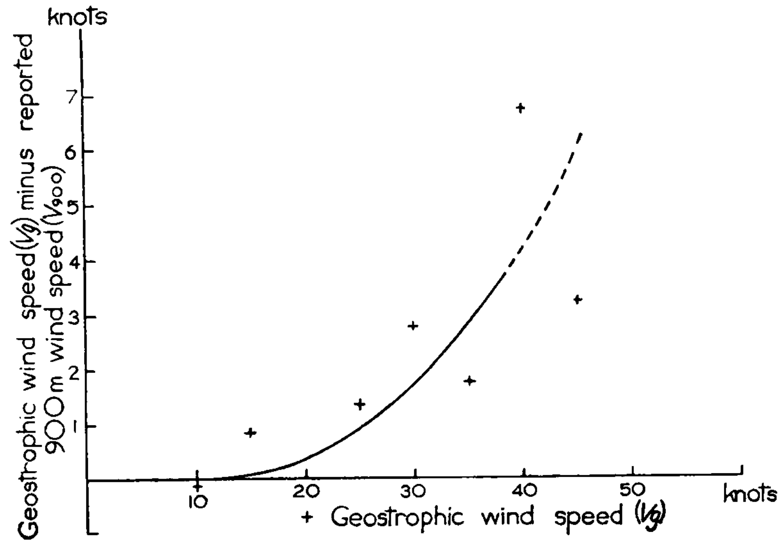


FIGURE 1—DIFFERENCE BETWEEN GEOSTROPHIC WIND SPEED AND REPORTED 900 M WIND WITH STRAIGHT STEADY ISOBARS

Nevertheless, there is undoubtedly a discrepancy between the two wind speeds which is small below 20 knots but increases rapidly with stronger winds. The cause appears to be that the 900 m speed is calculated from a horizontal displacement which takes place partly within the friction layer. The balloon rises at 350 m/min and the displacement is measured between the end of the first and third minutes, or sometimes between the first and fourth. The stronger the wind the greater will be the increase of speed with height and thus the greater will be the difference between the reported 900 m wind and the true speed. The magnitude of the discrepancies shown in Figure 1 is in quite good agreement with what is to be expected from the variations of speed with height found by pilot-balloon measurements.[1]

This explanation requires that there should be a corresponding discrepancy in direction, the reported 900 m wind being slightly backed from the true direction. Since radar wind directions are reported only to the nearest 10° a detailed analysis was not possible. Nevertheless a limited comparison for steady geostrophic winds of 35–40 knots showed the reported wind to be backed from the isobar by about 4° on the average.

The cyclostrophic term in steady anticyclonic flow.—It is not uncommon to find that anticyclonic isobars give a gradient wind speed markedly higher than the observed 900 m wind speed. It is then usual to suppose that the trajectory is straighter than the isobars because of the turning of the isobars as time goes on, as for example if there exists a small moving ridge. In order to ascertain whether a difference in speed could occur with little indication on the chart, a comparison was made on occasions of steady anticyclonic isobars. Steadiness was again defined by there being no change of geostrophic wind exceeding five knots in three hours in the vicinity of Crawley. Changes in curvature or direction in the three hours were ignored as these were usually small and were not thought to have any effect on mean values. Observations were taken from three winters.

Figure 2 compares the gradient wind with the reported 900 m wind speed. The crosses show means for every five knots of gradient wind speed, and the numbers of points used to obtain the means are shown in brackets. OA is the

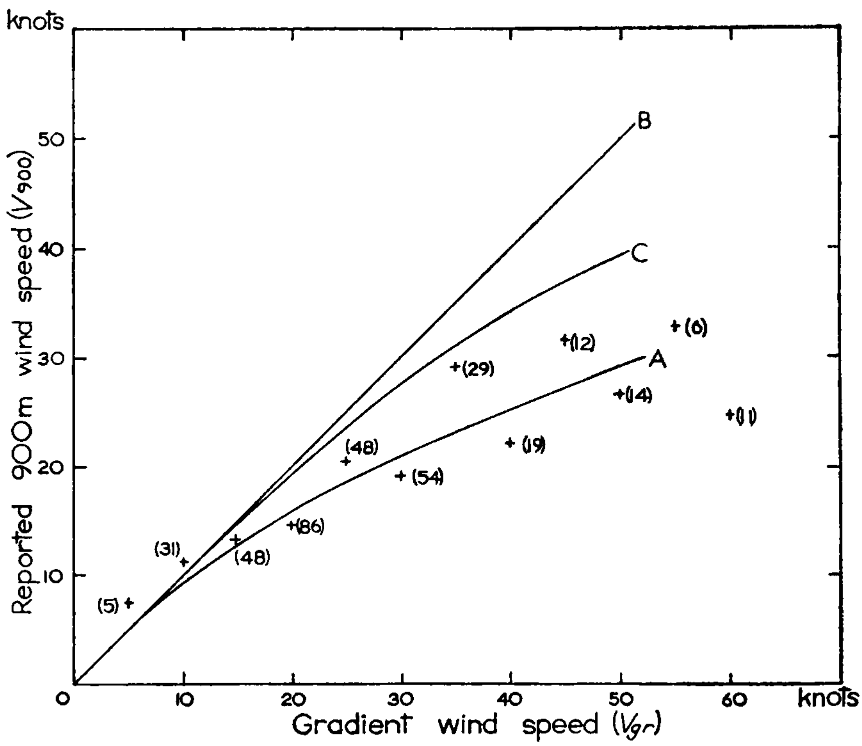


FIGURE 2—GRADIENT WIND SPEED COMPARED WITH 900 M WIND SPEED IN STEADY ANTICYCLONIC FLOW

line of best fit. (The alternation of the crosses about OA is due to the use of a limited number of radii of curvature, and through geostrophic winds being measured only to the nearest five knots.) The line OB would represent equality between the gradient wind and the reported 900 m wind speed, whereas OC, drawn from the data of Figure 1, represents the adjustment to OB for the systematic radar wind error.

Since OA is a substantial distance from OC, it is clear that the gradient wind speed, as determined from steady anticyclonic isobars, seriously over-estimated the true wind.

Figure 3 is based on the same set of observations, but here the geostrophic wind has been plotted instead of the gradient wind. The lines OA, OB and OC have the same significance as in Figure 2. It will now be seen that the mean geostrophic wind speed was within one or two knots of the true 900 m wind at all speeds. In other words, it appears that steady anticyclonic flow can be treated as though no cyclostrophic term exists. Whether this is true for all isobaric curvatures has yet to be determined.

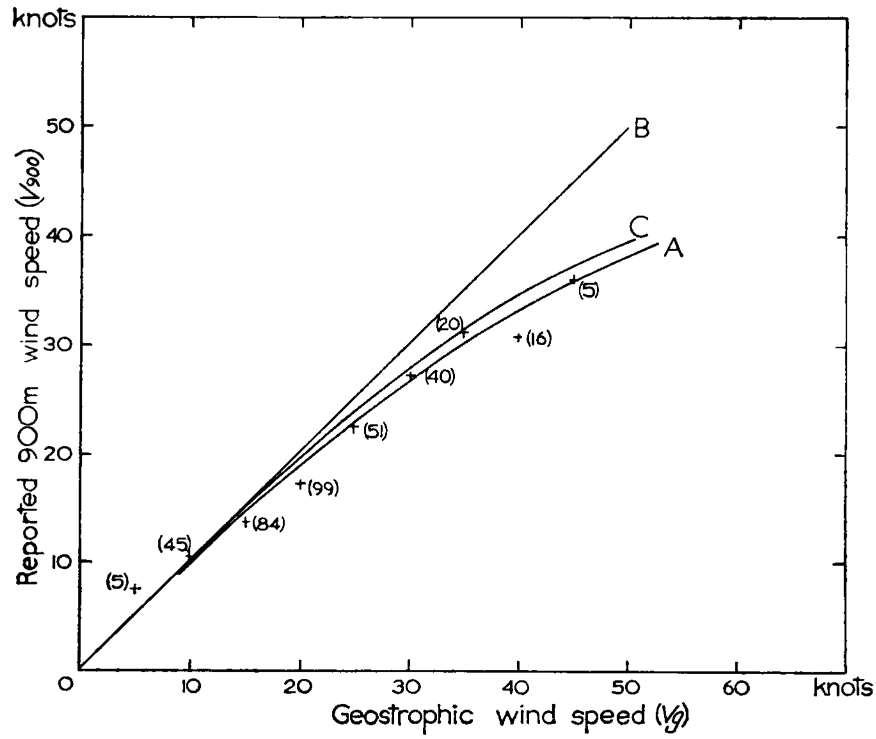
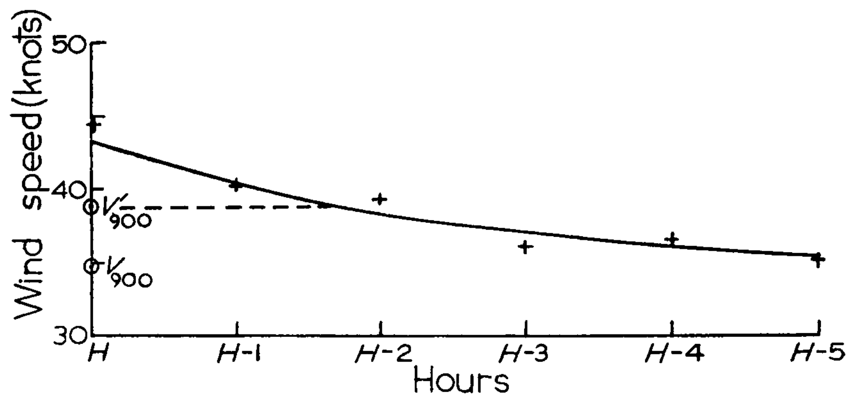


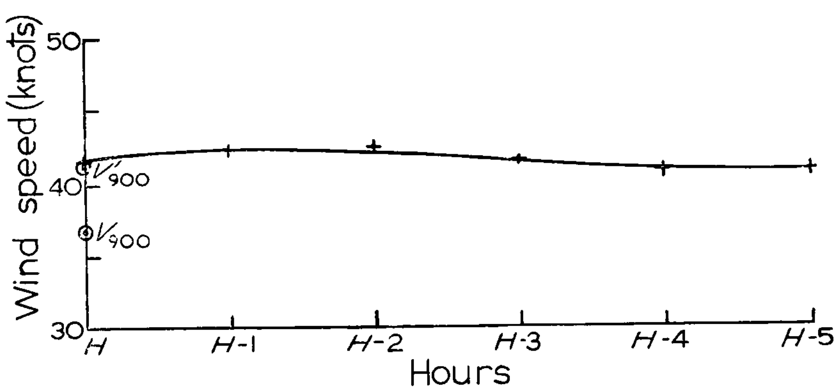
FIGURE 3—GEOSTROPHIC WIND SPEED COMPARED WITH 900 M WIND SPEED IN STEADY ANTICYCLONIC FLOW

The lag of the wind when the pressure gradient is changing.—In examining the lag of the wind behind a speed which matched the pressure gradient it was thought advisable to exclude cyclonic flow initially since this is complicated by movement of the isobars and by accelerations which are not well represented by the local change of pressure gradient. The investigation was therefore confined to straight and anticyclonic isobars, the assumption being made that since the cyclostrophic term was negligible in steady flow it could equally be disregarded when the pressure gradient was changing. In order to obtain an adequate amount of data, acceleration was defined by a geostrophic wind at least five knots stronger than it was three hours previously, and deceleration by it being at least five knots weaker. In view of the uncertainty of measurement by no means all the occasions appeared in the correct category, but the conclusions should be no less valid on that account.

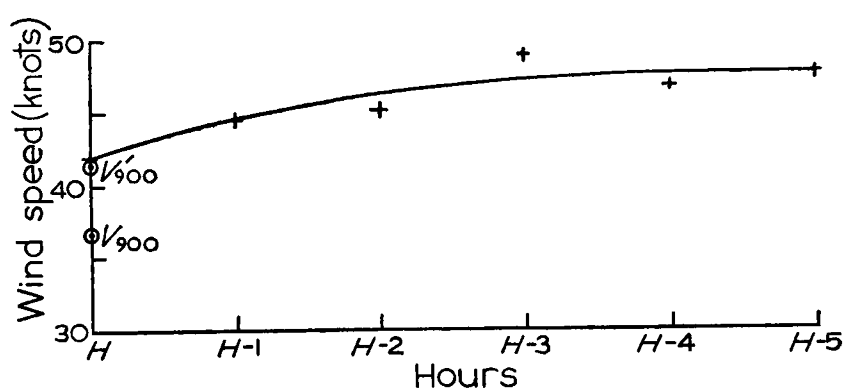
Figure 4 is based on all occasions in the winters of 1960–61 and 1961–62 when, with straight or anticyclonic isobars, the geostrophic wind at a major synoptic hour was at least 35 knots. Figure 4(*a*) shows, for 82 occasions of accelerating flow, the mean geostrophic wind at this hour (*H*) and at each of the five preceding hours. In drawing a smooth curve to fit the six points account has been taken of the fact that the method of selection introduces an artificially high mean geostrophic wind speed at *H* and an artificially low one at *H* − 3.



(*a*) Acceleration



(*b*) Steady flow



(*c*) Deceleration

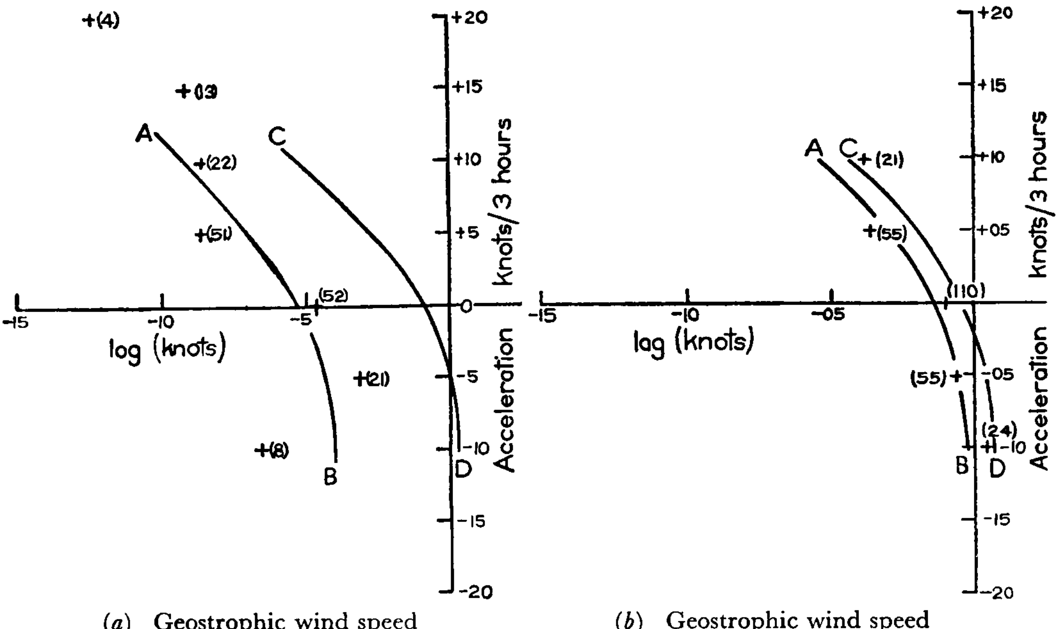
FIGURE 4—TIME LAG BETWEEN TRUE WIND SPEED AND GEOSTROPHIC SPEED FOR GEOSTROPHIC WIND SPEEDS OF AT LEAST 35 KNOTS

(The reverse occurs in Figure 4(*c*)). The reported 900 m wind speed (V_{900}) at *H* in accelerating air was 34·9 knots, compared with a geostrophic wind at the same time of 44·3 knots. The 900 m wind corrected for systematic error by Figure 1 was 38.9 knots (indicated by V'_{900}) and so was equal to the geostrophic wind nearly two hours before.

Figure 4(*c*), based on 37 occasions of deceleration, is of interest in that the mean geostrophic wind of 42.0 knots at the synoptic hour was accompanied by $V_{900} = 36.9$ and $V'_{900} = 41.6$ knots. Thus in decelerating air (and with a deceleration about two-thirds the magnitude of the acceleration shown by Figure 4(*a*)) the adjustment of the wind speed to the weakening pressure gradient was practically instantaneous. Figure 4(*b*), based on 51 pairs of observations, relates to geostrophic speeds unchanged over the three hours, and here $V_{900} = 36.9$ and $V'_{900} = 41.6$ knots, the latter being practically equal to the geostrophic speed at the time.

Similar results were obtained for geostrophic wind speeds between 20 and 30 knots though the duration of the lag was less certain because of the smaller slope of the curves.

The same wind observations were next analysed according to the magnitude of the 3-hour change in geostrophic speed. Figure 5(*a*) relates to geostrophic



(*a*) Geostrophic wind speed greater than 35 knots.

(*b*) Geostrophic wind speed between 20 and 30 knots.

FIGURE 5—LAG OF WIND IN RELATION TO ACCELERATION AS GIVEN BY LOCAL CHANGE OF GRADIENT WIND SPEED

winds of 35 knots or more at the synoptic hour, Figure 5(*b*) to winds between 20 and 30 knots. The ordinates show changes of speed in knots/3 hours and the abscissae the lag of the 900 m wind below the geostrophic speed. Curves AB relate to V_{900}, the reported 900 m wind speed, and curves CD to V'_{900}, the corrected 900 m wind. It was not possible to obtain more than rough curves AB because of the small number of changes exceeding five knots in three hours, and for this reason curves CD have been drawn simply by applying at all points the correction for the mean 900 m speed, correlation between speed and acceleration being ignored. The most that should be deduced from the curves CD is the rapid adjustment during deceleration and the fact that during acceleration the wind goes about half way towards meeting the 3-hour geostrophic wind increase. This lag is of course partly inherited at the beginning of the 3-hour period, as is seen from Figure 4(*a*), which shows that on the average a pressure gradient which increases does so for five hours or more.

The cyclostrophic term in relation to curvature.—So far only straight and anticyclonic flow have been considered, and for two reasons. It seemed likely that with this restriction the changes of pressure gradient experienced by a moving parcel of air would be satisfactorily represented by changes at a fixed point on its trajectory. Furthermore, the conclusion that the cyclostrophic term could be neglected in anticyclonic flow made it possible to assess the lag without taking curvature into account.

The next step was clearly to study the importance of the cyclostrophic term for a range of curvatures, both cyclonic and anticyclonic. Since cyclonic systems are usually more mobile than anticyclonic ones, the criteria adopted hitherto for acceleration or deceleration were unlikely to be so representative of the change in the motion of a parcel of air: trajectories were likely to diverge more from isobars than in anticyclonic flow, particularly when the curvature was large. Nevertheless, the same criteria were used for simplicity.

Data were extracted for the months October to March in the winters 1959–60, 1960–61 and 1961–62. The occasions chosen were those when the geostrophic wind speed was at least 35 knots at a major synoptic hour. (It was presumed that any relationships found would be similar in character for lighter winds.) The material tabulated comprised the 900 m wind speed, together with the geostrophic and gradient winds in the Crawley area for this hour and for each of the five preceding hours. The isobaric curvature, on which the gradient winds were based, was measured to the nearest of the following radii: 100, 150, 200, 250, 300, 400, 600, 800, 1000, 1200, 1500, 2000 and 3000 miles (nautical), both cyclonic and anticyclonic. Occasions when a trough passed over Crawley during the five hours were ignored. The flow was again regarded as steady when the geostrophic wind change over the last three hours was no greater than five knots.

A tabulation of winds in steady situations showed that some grouping of curvatures was necessary in order to provide enough observations in each group. Radii up to 300 miles were combined and listed as being 250 miles; 400 and 600 miles became 500 miles; and 1000 to 3000 miles were grouped as 1500 miles. Table I summarizes the mean wind speeds at the synoptic hours for each radius of curvature. (The corrected 900 m wind was obtained by applying the corrections of Figure 1 to the mean 900 m wind speed, but the gradient winds given are the means of individual readings.)

TABLE I—MEAN WIND SPEEDS IN RELATION TO CURVATURE IN STEADY SITUATIONS

	Cyclonic curvature				Straight	Anticyclonic curvature			
Radius of curvature (n. mile)	250	500	800	1500	isobars	1500	800	500	250
No. of observations	42	63	52	41	61	31	31	11	1
Reported 900 m wind speed (kt)	34·9	36·0	37·1	37·1	37·9	38·0	32·4	(30·4)	—
Corrected 900 m wind speed (kt)	38·9	40·3	42·0	42·0	43·1	43·2	35·4	(32·8)	—
Geostrophic wind speed (kt)	43·4	43·6	42·2	42·8	43·1	42·2	38·5	(37·5)	—
Gradient wind speed (kt)	32·0	36·6	37·7	39·1	43·1	45·9	45·4	(51·3)	—

The figures of Table I are plotted in Figure 6. It will be noted that on the anticyclonic side the geostrophic wind appears even to over-estimate the true wind speed. On the cyclonic side the cyclostrophic component was negligible when the radius of curvature was 800 miles or more. For a radius of 500 miles about one-third the cyclostrophic reduction was appropriate, and at 250 miles about one-half, allowing in both cases for some smoothing of the curve.

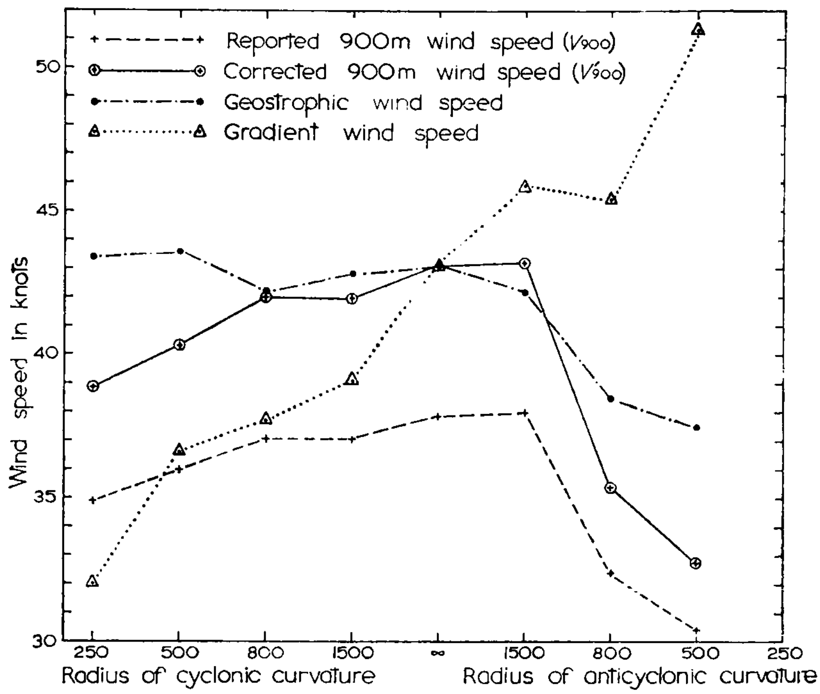


FIGURE 6—MEAN WIND SPEED RELATIONSHIP TO RADIUS OF CURVATURE OF ISOBARS DURING STEADY FLOW WITH GEOSTROPHIC WIND SPEEDS OF AT LEAST 35 KNOTS

The lag of accelerating or decelerating air with straight or cyclonic isobars.—An analysis was made of accelerating flow to ascertain what modification was necessary to Table I and Figure 6 when there was a 3-hourly increase of geostrophic wind of at least 10 knots. The results for cyclonic and straight isobars are given in Table II.

TABLE II—MEAN WIND SPEEDS IN RELATION TO CURVATURE DURING ACCELERATION

	Cyclonic curvature				Straight
Radius of curvature (n. mile)	250	500	800	1500	isobars
No. of observations	16	17	12	28	23
Reported 900 m wind speed (kt)	37.4	39.5	38.1	40.1	37.0
Corrected 900 m wind speed (kt)	42.3	45.6	43.3	46.7	41.8
Geostrophic wind speed (kt)	63.5	52.7	51.7	51.4	48.5
Gradient wind speed (kt)	42.1	42.7	45.2	47.2	48.5
Empirical gradient wind speed (kt)	52.8	49.4	51.7	51.4	48.5
Empirical less corrected 900 m speed (kt)	10.5	3.8	8.4	4.7	6.7

The corrected cyclonic 900 m wind is in good agreement with the gradient wind. This result is almost certainly fortuitous, though it can be accepted as a convenient forecasting rule. The lag in straight flow being 6.7 knots, which is consistent with Figure 4(*a*) (for which the criteria were slightly different), it is clear that some such lag must occur at all curvatures.

In order to isolate the lag for each radius of curvature, an 'empirical gradient wind' was computed for each column on the basis of the reduced cyclostrophic component found appropriate in steady flow. This empirical gradient wind and its difference from the true wind are given in the last two rows of Table II. As mentioned earlier, geostrophic wind measurements are a little higher than true mean values because of the criterion for acceleration, so four or five knots is perhaps a reasonable average lag for radii of 500 miles or more. There is little doubt that the lag is greater for radii of 250 miles, and this is presumably accounted for largely by the inadequacy of the criterion for acceleration. An increasing gradient and very curved isobars imply that on the average the air has come from a place where the gradient and the flow are weaker, particularly when the wind is backing with time. With pronounced curvature the lag therefore includes a quantity corresponding to the increase in gradient wind along the trajectory: in other words, when the curvature is large the acceleration begins from a relatively low speed.

The same analysis was attempted for decelerating flow but there were insufficient observations to furnish a similar table. Moreover, some of the mean winds were too high for the corrections of Figure 1 to be applied. Nevertheless, it appeared that the corrected 900 m wind was about equal to the empirical gradient wind.

Since the last line of Table II suggested that the lag of accelerating air did not depend on the radius of curvature until this was as low as about 250 miles, it seemed reasonable to group together all remaining occasions of cyclonic flow in order to construct a diagram corresponding to Figure 4(*a*). This was done for all 5-hour periods during which the radius of isobaric curvature was at least 400 miles. The average of 46 such periods is shown in Figure 7. Although

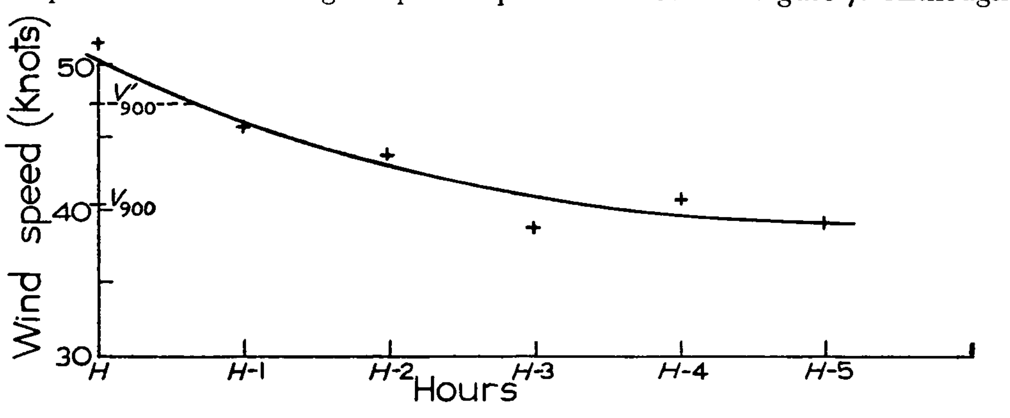


FIGURE 7—TIME LAG BETWEEN TRUE WIND AND 'EMPIRICAL GRADIENT WIND' SPEED

For geostrophic wind speeds accelerating to at least 35 knots and with radius of isobaric curvature (cyclonic) of at least 400 miles.

we know that measured geostrophic winds (and therefore empirical gradient winds) are biased in opposite directions at times H and $(H - 3)$, because of the acceleration criterion, the curve leaves little doubt that in this relatively strong and intensifying cyclonic flow the time lag of the wind was less than for straight or anticyclonic isobars. Whether the lag of less than an hour, as compared with 1½–2 hours for straight or anticyclonic flow, should be regarded as a consequence of higher winds, greater acceleration or the shape and movement of the isobars cannot easily be determined.

Summary of results.—

(i) The 900 m wind speed in British radar reports is an underestimate, the error increasing with speed as shown in Figure 1.

(ii) With straight or anticyclonic isobars, the pressure gradient being unchanging or weakening, the 900 m wind speed is equal to the geostrophic. The cyclostrophic component is negligible.

(iii) With straight or anticyclonic isobars and an increasing pressure gradient, the 900 m wind speed is equal to the geostrophic speed of 1½–2 hours ago.

(iv) In cyclonic flow, with an unchanging or weakening pressure gradient, the 900 m wind speed is equal to the geostrophic speed when the radius of isobaric curvature is at least 800 miles. With a radius of curvature of roughly 500 miles about one-third the cyclostrophic correction is appropriate, and one-half for a radius of about 250 miles. This result is based on wind speeds of 35 knots or more.

(v) In accelerating cyclonic flow the 900 m wind speed is as given by (iv) above, but with a time lag of rather less than one hour; except that for radii of isobaric curvature of about 250 miles the wind speed is still lower by a few knots. A fortuitous alternative method of estimating the wind speed is to disregard the time lag and apply the full cyclostrophic correction for isobaric curvature. These results were based on wind speeds of 35 knots or more.

Discussion.—No reasonable explanation was found of the fact that the adjustment between wind speed and pressure gradient depends on whether the gradient is increasing or decreasing. Vertical stability did not seem an important factor since acceleration and deceleration were not significantly related to wind direction. Equally there were not any differences in the average rate of turning of the isobars, which would have introduced different cyclostrophic components.

The apparent unimportance in steady flow of the cyclostrophic term, as illustrated in Figure 6, was first examined as a possible result of vertical transfer of momentum. However, the average vertical shear between 900 m and 850 mb was found to be much the same in both cyclonic and anticyclonic flow, so this factor was discarded.

The most feasible explanation is that the trajectories of the air were significantly different in curvature from the isobars. With no local change in the magnitude of the pressure gradient over three hours it seemed that the departure of the trajectories from the isobars must come from turning of the isobars.

The radius of curvature of a trajectory is related to the radius of a streamline in a formula ascribed by Petterssen[2] to Blaton:

$$\frac{1}{r_T} - \frac{1}{r_s} = \frac{1}{V}\frac{\partial\beta}{\partial t}$$

where r_T = radius of curvature of the trajectory,

r_s = radius of curvature of the streamline, here assumed to coincide with the isobar,

V = wind speed,

$\frac{\partial\beta}{\partial t}$ = local rate of turning of the wind, here taken to be the direction change in the last three hours.

The average backing or veering of the isobars was calculated for each radius of curvature included in Figure 6. On the cyclonic side the adjustment to the cyclostrophic component was negligible, the largest being an increase of one knot at 250 miles radius of curvature. There was also practically no correction required for straight isobars. On the anticyclonic side there was a backing of the isobars at all three radii, the average rate being 1.5°/hr. This was sufficient to give at each radius of curvature a cyclostrophic wind component equal to about half the component found from the isobars. A surprising fact was that the same calculation for accelerating cyclonic flow gave similar results to those for steady cyclonic flow. Thus it appears that the different wind speed relationships between steady and mobile cyclonic situations arise not through differences of isobaric turning but because, as mentioned earlier, the pressure gradient changes significantly along the trajectory. This argument is not conclusive because in the formula given above the curvature of the streamline has been assumed equal to the curvature of the isobar, and this is not strictly true during acceleration.

Reverting to relationships in the steady state, as given by Figure 6, another explanation of the disappearance of most of the cyclostrophic component in cyclonic flow, and of half of it in anticyclonic flow, must be sought. In speculating on the cause it may be recalled that Zobel[3] and others have found the wind speed at high levels to be closer to the gradient wind speed than to the geostrophic speed.

A possible solution may lie in the meso-structure of the air flow. It may be that what is regarded on the synoptic scale as smooth, circular flow is in fact somewhat discontinuous, the circle being an approximation to a series of fairly straight paths linked by small troughs or ridges. If this were so the wind speed would be close to geostrophic if the air rounded the troughs or ridges so quickly that only partial adjustment to gradient speed was possible. This could come about in one of two ways, or through a combination of both. An isobar which appears on a chart to be smoothly curved may normally tend towards a polygonal shape, and indeed a close network of reliable pressure readings brings to light many unsuspected irregularities in an isobaric pattern. Alternatively the troughs and ridges in a flow may represent the more pronounced waves in a series of oscillations about an equilibrium line, most of the oscillations resulting in very minor deviations from straight flow and the main turning of the wind being effected by isolated waves.

Supporting evidence for these speculations is hard to find, chiefly because large curvature usually involves the complexities of a fluid situation. It is of interest, however, to note the observations on the variations of wind speed with time, some of which have been summarized by Durst.[4] The standard vector deviation of wind over one place increases fairly steadily with time after the first hour or so, but within the first hour there is a disproportionately high variation even after allowance has been made for observational errors. This may be evidence of irregular flow such as is suggested in the previous paragraph.

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A SCALE FOR MINIMUM RADIUS OF CURVATURE OF ANTICYCLONIC FLOW

By G. J. JEFFERSON, M.Sc.

The routine preparation of forecast upper air charts suggests that some safeguard is necessary to prevent the drawing of anticyclonic curvature with winds too strong to give a real solution to the gradient wind equation. This article describes the computation of a scale to do this which is in practical use on the forecast bench at London (Heathrow) Airport. The chart used for upper air analysis and forecasting, Form 2219B, is a conformal conical projection with two standard parallels at 30°N and 60°N to a scale of $1:15\times10^6$. Broadly speaking the forecast area lies between latitudes 30°N and 70°N for which contours and isotachs are produced at standard levels. One of the most important features of these charts is the placing of jet streams and maximum-wind belts and it is with these strong winds that the critical radius is large and the safeguard most necessary.

The gradient wind equation for anticyclonic curvature is

$$\frac{V^2}{r} - fV + fG = 0 \qquad \ldots (1)$$

where V = the gradient wind, G = the geostrophic wind, f = the Coriolis parameter $2\omega \sin \varphi$, and r = radius of curvature of the air trajectory.

$$\text{Thus } V = \frac{fr}{2} \pm \frac{fr}{2}\sqrt{\left(1 - \frac{4G}{fr}\right)}. \qquad \ldots (2)$$

There is therefore a minimum value of r which will provide a real solution to the equation. When r is less than this no balance of forces is possible since the cyclostrophic term together with the pressure gradient force becomes too great to allow a balance with the Coriolis term.

The critical condition is therefore:

$$fr = 4G \qquad \ldots (3)$$

$$r = \frac{2G}{\omega \sin \varphi}$$

$$= \frac{7.62G}{\sin \varphi},$$

where r is expressed in nautical miles and G in knots.

Table I columns (a) show the value in nautical miles of the minimum possible values for r for balanced motion with winds from 40 to 200 knots in latitudes 30°N to 70°N. As shown by Freeman[1] these radii must be corrected for map distortion. He has shown that the amount of correction of radius of curvature due to this cause varies not only with the magnitude of the radius and with the latitude, but also with the approximate wind direction, and he evaluates three cases—north–south flow, and east–west flow concave to north and convex to north. Since we are dealing mainly with the upper westerlies, anticyclonic curvature is most commonly convex approximately northwards. Accordingly the values of columns (a) in Table I have been corrected from smooth curves drawn from Freeman's values of r_x in his Table I.[1] These are shown in columns (b) of Table I and are the actual values of the critical radii of ridges with a north–south axis in nautical miles as measured on the conformal conic projection with standard parallels at 30°N and 60°N.

TABLE I—CRITICAL RADII IN NAUTICAL MILES

Latitude	Wind speed in knots: 40 (a)	40 (b)	50 (a)	50 (b)	60 (a)	60 (b)	80 (a)	80 (b)	100 (a)	100 (b)
70°N	325	330	405	410	486	490	648	735	810	770
60°N	352	340	440	425	528	506	704	680	866	810
50°N	400	380	500	490	600	578	800	770	1000	965
40°N	480	475	600	590	720	700	960	954	1200	1260
30°N	610	650	762	780	914	1020	1220	1400	1524	1760

Latitude	Wind speed in knots: 120 (a)	120 (b)	140 (a)	140 (b)	160 (a)	160 (b)	180 (a)	180 (b)	200 (a)	200 (b)
70°N	972	890	1134	990	1296	1070	1458	1200	1920	1460
60°N	1056	970	1232	1060	1408	1260	1580	1380	1732	1500
50°N	1200	1160	1400	1350	1600	1500	1800	1700	2000	1900
40°N	1440	1508	1680	1780	1920	2005	2124	2250	2400	2550
30°N	1828	2180	2133	2550	2440	2980	2743	3400	3048	3870

(*a*) calculated (*b*) corrected for map distortion.

However, the conformal conic projection is orthomorphic, i.e. the scales of distance along the meridians and parallels are equal at any point. The scale is constant along the parallels but varies with latitude, being correct at 30°N and 60°N, too small between them and too great outside them. The measurement of distances in a north–south direction therefore must involve a small loss of accuracy if the scale at any given latitude is used. Since the radii are, in this case, measured along the meridians the variation of scale is obviously of greatest importance with strong winds and large critical radii. As a first approximation therefore the scale at latitudes of the mid-points of the radii has been taken for the actual measurements on the chart.

The scale of this chart (Form 2219B) in any latitude φ is given by the formula

$$\frac{1 + \sqrt{3}}{30 \times 10^6 (\sin \varphi + \cos \varphi)}$$

which has been used to evaluate the critical radii in inches shown in Table II, which for practical reasons has been taken down to only 40°N.

TABLE II—RADII IN INCHES CORRECTED FOR SCALE TAKING LATITUDE OF MID-POINT OF RADIUS OF CURVATURE

Latitude °N	Wind speed in knots: 40	50	60	80	100	120	140	160	180	200
70	1.66	2.04	2.46	3.14	3.80	4.33	4.73	5.20	5.85	7.06
60	1.59	2.02	2.40	3.22	3.80	4.53	4.98	5.80	6.56	7.02
50	1.77	2.28	2.69	3.58	4.46	5.46	6.36	7.10	8.07	9.05
40	2.26	2.79	3.32	4.55	6.14	7.40	8.88	10.01	11.60	13.50

Fortunately in the relatively high latitudes, say 60°–70°N where the peaks of most jet-stream ridges occur, it can be readily seen from Table II that the critical radius on the chart shows little change with latitude. Furthermore, on account of the variation of the scale of the chart with latitude, one geostrophic scale will also serve. Figure 1 has therefore been produced as a geostrophic scale which also shows the critical radii which will apply without appreciable loss of accuracy between about 55°N and 75°N, which is the region where it is most commonly required. Measured critical radii are considerably greater in lower latitudes and Figure 2 shows an additional scale for 50°N which would be suitable for use down to about 45°N and will cover most other ridges for which a scale would be required.

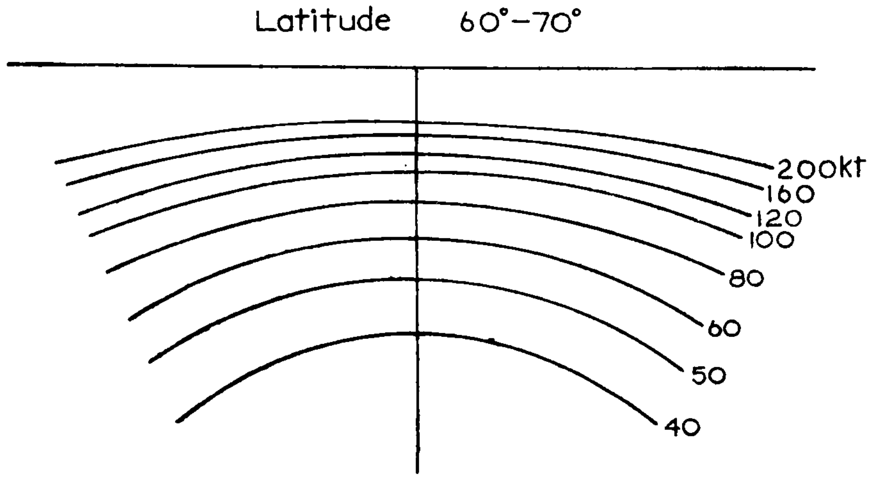

FIGURE 1—GEOSTROPHIC SCALE SHOWING CRITICAL RADII FOR LATITUDE 60–70°N
For contour interval 120 metres

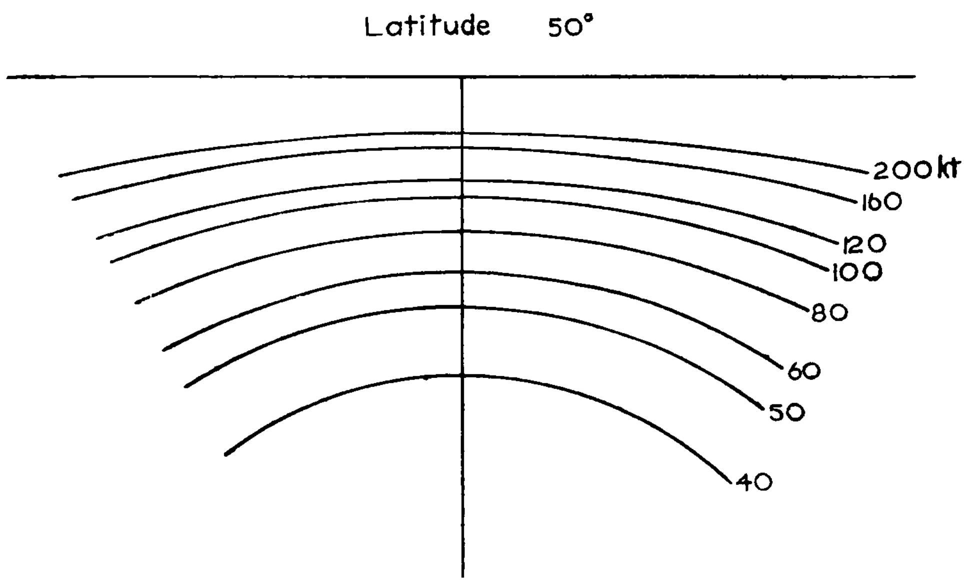

FIGURE 2—GEOSTROPHIC SCALE SHOWING CRITICAL RADII FOR LATITUDE 50°N
For contour interval 120 metres

In drawing isotachs on a forecast upper air chart this scale has an additional use. When r has the critical value for anticyclonic curvature it follows, from substituting equation (3) in equation (2), that

$$V = 2G.$$

Therefore, in using the scale on contours of about the critical radius of anticyclonic curvature, it is known that the gradient wind to be expected round the crest of the ridge will be twice the value read from the scale. The scale thus ensures, not only that the critical curvature will not be exceeded, but also that adequate allowance is made for the cyclostrophic term when it is not.

In using such a scale it must be remembered that it has been evolved from the gradient wind equation which is based on air trajectories. Strictly speaking it can therefore only be applied directly to contours or streamlines of a stationary system. Any system moving in the same direction as the air flow will give a larger radius for trajectories than for streamlines. Since the main use of the scale is with jet cores and maximum-wind belts, the speed of movement of the system will usually be only a small fraction of the wind speed so that the loss of accuracy in using the scales with contours or streamlines is of less importance than might appear at first sight.

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THE COMPUTATION OF MONTHLY SUMMARIES OF WINDS FROM INCOMPLETE DATA

By D. DEWAR, B.Sc.

Summary.—A description is given of statistical tests carried out to decide which of two methods, recommended in the *Guide to Climatological Practices*,[1] for computing mean values for combined hours of observations should be used in the production of routine summaries of upper winds by electronic computer. Conclusions reached and some further applications of the results are given.

Introduction.—There are three simple methods of computing combined hours values of an element:

(*a*) to compute a daily mean value for each day from values at different hours and then to take the mean of these values as the combined hours mean value for the month;

(*b*) to compute a monthly mean for each hour of observation and then take the mean of these as the monthly mean;

(*c*) to divide the sum of all available values by the number of observations.

The *Guide to Climatological Practices* recommends the use of either method (*a*) or (*b*). The computer programme had been drawn up to produce summaries by both methods (*a*) and (*c*) and there were sometimes appreciable differences between values computed by the two methods when there were missing observations at high levels. To provide data upon which to base a decision as to the method to be used for future routine work, modifications were made to the programme so that, after the normal monthly summary had been produced, the data already in the computer could be used to compute vector mean winds by each of the methods (*a*), (*b*) and (*c*), using distributions obtained by omitting a random selection of data from originally complete distributions at the lower levels for which the true values were known.

Random selection procedure.—The procedure adopted was as follows. Only data for the first 10 levels (surface to 250 mb) of an ascent were used. These provided 10 complete distributions for each of which random selections

Photograph by Mr. R. K. Pilsbury

METEOROLOGICAL OFFICE HEADQUARTERS BUILDING

Taken at 1215 GMT on 25 January 1963 after a night when rime was heavily deposited on the trees.

Photograph by Mr. F. A. Gordon

ICE GROWTHS FORMED ON GRASS STALKS

This photograph was taken near the Meteorological Research Flight buildings at Farnborough on 25 January 1963. The thick 'hump-backed' and corrugated formations resulted from water splashing from a burst pipe in the roof above.

Photograph by Mr. F. A. Gordon

An enlargement of part of the photograph (left) showing the peculiar 'caterpillar'-like structure of the ice on the vertical stalks.

Photograph by Mr. E. M. K. Kirk

AN UNUSUAL ICE FORMATION PHOTOGRAPHED AT BRIDGNORTH ON 25 JANUARY 1963

Steam from the heating system is fed back into a condensate tank surrounded by an asbestos housing the bottom of which is seen at the top of the photograph. Much of the steam condensed on the housing forming icicles, but some water dripped on to the handle of a board below forming what was known locally as 'the ice plant'.

of data to be regarded as missing were made by the computer. A random selection of dates for which data were to be considered missing for all hours was made first and was followed by random selections of individual missing values either in one stage or two stages; the first stage selections, obtained by random selection of data from all four hours of observations, had roughly the same number of observations at each hour and were used for what are referred to later in this note as series A tests; the second stage selections taken from two of the hours of observations only, had considerably fewer observations at 0600 and 1800 GMT than at 0001 and 1200 GMT and were used for series B tests. The number of selections made was arranged so that the resulting incomplete data roughly simulated actual high level observations from the point of view of missing data.

Computations.—Using combined hours data for each of the ten levels in turn and omitting 'missing values', the vector mean wind, standard vector deviation, average wind speed and the vector difference between the vector mean winds for complete and incomplete distributions were computed and printed together with the number of observations used. For computing standard vector deviations, components computed by method (*a*) and mean sums of squares computed in an analogous manner were used.

Conclusions drawn from the results.—Detailed tables of the results have been set out and discussed in a *Climatological Memorandum*.[2] In this note only a summary of the results and conclusions drawn from them are given.

Tests using data for Lerwick for March 1959.—Ten sets of tests for ten levels were carried out using these data. Two of these were series A tests, the number of observations after the omission of randomly selected data varying from about 22 to 25 at each hour; eight were series B tests with observations varying roughly from 12 to 20 at two of the four hours of observations and from 22 to 25 at the other two hours.

The merits of the three methods were compared using three criteria—totals ofmean vector errors at each level; maximum vector errors in any test; number of occasions when vector errors were: (i) less by method (*a*) than by method (*b*) and (ii) less by method (*c*) than by method (*b*).

Results showed that for distributions of this type the use of method (*a*) gave better results than method (*b*) as regards all three criteria, the differences being most marked for the series B tests. Method (*c*) gave slightly worse estimates of the values than method (*b*) in the series A tests but appreciably better estimates in the series B tests.

Tests using data for Aldergrove and ocean weather station Juliett.—Three series A tests and six series B tests were carried out using data for Aldergrove and one series A and two series B tests using data for ocean weather station Juliett.

The results confirmed the conclusions based on the tests using values for Lerwick; method (*a*) again gave, in general, the best estimates of the true values, the departures being most marked for the series B tests. In the series A tests there was little to choose between estimates of the true values obtained by methods (*b*) and (*c*) but in the series B tests method (*c*) gave, on the whole, definitely better estimates.

TABLE I—VALUES AND ERRORS OF ESTIMATES OF $\mathbf{V}_R$ AND S.V.D. USING INCOMPLETE 100 MB WIND DISTRIBUTIONS

Lerwick

Year	Month	Missing obs. 0001 GMT	Missing obs. 1200 GMT	Incomplete values $\mathbf{V}_R$ *degrees*	Incomplete values $\mathbf{V}_R$ *kt*	Incomplete values s.v.d. *kt*	s.v.d. error *per* cent*	$\mathbf{V}_R$ Vector error *kt*	$\mathbf{V}_R$ Vector error φ
1959	Jan.	—	—	—	—	—	—	—	—
	Oct.	1	5	277	11.9	18.7	0.5	0.3	1.6
	Nov.	2	2	244	16.4	20.6	1.0	0.7	3.1
	Dec.	1	3	251	26.5	22.8	0.4	0.0	0.0
1960	Jan.	1	4	301	24.8	27.4	2.5	0.4	1.5
	Oct.	1	5	281	7.2	11.6	5.7	0.7	6.0
	Nov.	6	4	272	13.1	18.2	2.8	0.6	3.3
	Dec.	10	7	276	19.6	18.9	3.6	1.3	6.9
1961	Jan.	6	6	271	23.9	18.7	0.5	1.5	8.0

Stornoway

Year	Month	Missing obs. 0001 GMT	Missing obs. 1200 GMT	Incomplete values $\mathbf{V}_R$ *degrees*	Incomplete values $\mathbf{V}_R$ *kt*	Incomplete values s.v.d. *kt*	s.v.d. error *per* cent*	$\mathbf{V}_R$ Vector error *kt*	$\mathbf{V}_R$ Vector error φ
1959	Jan.	4	6	288	42.2	27.1	2.7	2.1	7.7
	Oct.	4	1	271	14.1	24.8	0.4	0.8	3.2
	Nov.	9	10	250	16.3	20.5	0.5	0.4	2.0
	Dec.	3	11	258	17.2	22.7	1.8	1.4	6.2
1960	Jan.	3	6	293	21.2	26.9	1.5	1.6	5.9
	Oct.	6	5	294	7.2	12.8	0.8	0.8	6.3
	Nov.	8	4	266	17.8	16.9	0.6	1.6	9.5
	Dec.	10	9	278	22.8	20.0	2.9	1.1	5.5
1961	Jan.	13	10	270	23.5	18.3	8.5	1.8	10.1

Crawley

Year	Month	Missing obs. 0001 GMT	Missing obs. 1200 GMT	Incomplete values $\mathbf{V}_R$ *degrees*	Incomplete values $\mathbf{V}_R$ *kt*	Incomplete values s.v.d. *kt*	s.v.d. error *per* cent*	$\mathbf{V}_R$ Vector error *kt*	$\mathbf{V}_R$ Vector error φ
1959	Jan.	7	8	289	38.2	30.9	10.4	3.9	13.9
	Oct.	2	5	304	13.7	20.3	1.5	0.9	4.3
	Nov.	2	2	267	13.7	19.2	1.6	0.3	1.7
	Dec.	10	10	275	25.3	27.8	12.2	3.7	15.0
1960	Jan.	8	6	300	20.5	23.2	10.8	3.4	16.4
	Oct.	—	—	—	—	—	—	—	—
	Nov.	—	—	—	—	—	—	—	—
	Dec.	2	3	295	15.0	23.1	2.2	1.6	7.0
1961	Jan.	3	4	295	19.2	17.5	5.7	2.3	13.9

* expressed as percentage of incomplete distributions s.v.d.

φ vector error expressed as percentage of incomplete distribution s.v.d.

TABLE II—MISSING WINDS AT 100 MB — SPEED FREQUENCIES

Speed range (kt)	0–9	10–19	20–29	30–39	40–49	50–59	60–69	70–79	80–89
Complete distribution	192	415	365	295	209	106	52	17	6
Missing observations	19	49	56	54	38	14	18	7	3
Percentage lost	10	12	15	18	18	13	35	41	50

Tests using data for Aden for March 1959.—In order to see how results by each method compared when used with a distribution in which there was considerable variation of wind direction with height (a type often experienced in the British Isles in summer), tests were carried out using winds for Aden. In the series A tests where there were roughly the same number of observations at each hour (only two ascents a day were made at Aden) method (*a*) was rather better than either of the other two methods. In series B tests, with considerably more observations at one hour than at the other, method (*a*) was definitely worse than method (*b*) when using data for the surface and 900 mb levels where there was usually a marked diurnal variation of wind; at higher levels method (*a*) gave, on the whole, better estimates than method (*b*). Results using method (*c*) were very similar to those obtained by method (*a*).

Further discussion of results.—Results of the tests were used to make some deductions as to the possible accuracy of estimates of the standard vector deviation and vector mean wind obtained from incomplete data. Data from a carefully planned series of statistical tests would have been better; a decision as to which method should be used was urgently required however, and the modifications made to the existing programme were of a rather impromptu nature designed only to give comparative results for the three methods.

The maximum errors of estimates of the standard vector deviation (s.v.d.) were expressed as percentages of the true s.v.d. and it was found that, if the s.v.d. of the incomplete distribution is taken as being an approximation to the true value, the error will only occasionally be more than 10 per cent and will often be not more than 5 per cent.

The maximum vector errors of estimations of the vector mean wind ($\mathbf{V}_R$) were also expressed as percentages of the s.v.d. of the appropriate incomplete distribution, and it was found that maximum errors of from 10 to 20 per cent of the s.v.d. of the incomplete distribution may be expected; for distributions of the Lerwick or Aldergrove type used in the tests maximum errors are likely to be 10 to 15 per cent of the s.v.d. if the numbers of observations at different hours are unequal but only 5 to 10 per cent if the numbers are about the same; for the Aden type of distribution, which shows a considerable variation of wind with height, maximum errors of 15 to 20 per cent are often likely.

Applicability to actual data.—After reading *Climatological Memorandum No.* 34 C. L. Hawson suggested that it was doubtful whether results based on a random selection of missing data would apply to actual incomplete data at high levels where, in winter, recorded values are regarded as being strongly biased in favour of light winds as a result of selective factors operating to eliminate strong winds during an ascent.

A limited investigation was carried out using winds at 100 mb to form an idea of the effect of such losses. Days when winds were missing at 100 mb from ascents made at 0001 and 1200 GMT at Lerwick, Stornoway and Crawley in January, October–December 1959 and 1960, and in January 1961 were noted and estimates of the 258 missing winds were made from 100 mb upper air charts. The monthly mean winds and standard vector deviations were computed for the 'completed' distributions, and errors of corresponding values for the incomplete distributions were expressed as percentages of the appropriate incomplete distributions. Results are shown in Table I.

It will be seen that the conclusions regarding likely errors of the s.v.d. computed from an incomplete distribution resulting from purely random losses, namely, 'the error will only occasionally be more than 10 per cent and will often be not more than five per cent', apply remarkably well to these tests also.

Errors of the vector mean wind also are similar to those found in the random tests using data for Lerwick and Aldergrove, only one being greater than 15 per cent, but they do not show the same relation to equality or otherwise of the number of observations at the different hours. This is no doubt because losses of very strong winds which cause large errors may be expected at successive hours of observations and this tends to equalize the number of observations.

It seemed likely that the general agreement between results for purely random losses and actual losses at 100 mb could be ascribed to the fact that strong winds in the troposphere are usually associated with light winds in the stratosphere, and that this leads to the actual losses approximating to random losses. To examine this supposition, frequencies of wind speeds (in 10-knot ranges) were extracted for the complete distribution and for the missing winds. The results are shown in Table II. Up to speeds of about 60 kt the percentage losses, though increasing with speed, did not depart very much from purely random values (about 14 per cent for each range). At higher speeds the losses were highly selective, but the number of occasions when there were observations in these ranges was small (75 out of 1657 observations) and this resulted in total losses being similar to random losses.

These investigations showed that at 100 mb although there was a selective loss of winds, the results of the random tests could have been used to get an idea of the likely errors of the vector mean winds and standard vector deviation computed from the remaining observations. How far this would apply to data for still higher levels is uncertain as presumably selective losses increase with height producing distributions which become less and less random; a tentative suggestion is that, as long as the number of missing observations (and other parameters) are similar to those of the random tests, errors of estimates made from the remaining data may be expected to be similar to those found in the random data tests.

Conclusions.—For routine summaries of upper winds produced by an electronic computer, where the arithmetic involved is a minor consideration and unique instructions are required, the use of method (*a*) for the computation of combined hours summaries of wind is recommended. If arithmetic is a consideration the use of method (*b*) can be regarded as satisfactory when there are roughly the same number of observations at each hour. For summaries of an element for which the diurnal variation is greater than the interdiurnal variation, method (*b*) should be used.

Rough estimates of the maximum vector error of a vector mean wind computed from an incomplete distribution can, subject to certain restrictions, be made from the standard vector deviation of the incomplete distribution.

Acknowledgement.—The author is indebted to Mr. P. B. Sarson for help with the random selection procedure and to Mr. F. E. Lumb for some very helpful criticism and suggestions during the preparation of this note.

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THE HOUGHALL FROST HOLLOW

By A. J. W. CATCHPOLE, B.Sc.
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Introduction.—Frost hollows are common features of the British landscape but the opportunities for studying their climatic conditions are limited. Valley bottoms and basins are often poor sites for meteorological stations since they produce the extremes which must be avoided by the normal observer. Some fairly long-term records from frost hollows do exist however and these can be used to describe the seasonal variations in these extremes. In this way a valuable reference is provided for the large amount of short-term experimental work which is being done in frost hollows. The account of the Rickmansworth frost hollow by Hawke[1] is particularly outstanding. Using a 13-year record of temperature from the Chess Valley Hawke was able to demonstrate the relative continentality of the thermal conditions at Rickmansworth. In this paper a comparison will be made between the temperature records in the Houghall frost hollow and those of a neighbouring summit station at Durham. Later, brief comparisons between the conditions at Houghall and Rickmansworth will be drawn.

The stations.—The locations of the climatological stations at Houghall Agricultural College and Durham Observatory are shown in Figure 1. Houghall lies roughly 200 feet below Durham and less than a mile distant to the south-east. The site of Durham Observatory and its meteorological record have been described in detail by Manley.[2] Briefly, it occupies an open summit on a plateau surface into which the Wear is entrenched by some 200 feet. Houghall is located on this valley floor at a point where it is flanked by steep escarpments at the edge of the plateau. The only extensive woodland in the area is on these escarpments. The remainder of the area is fairly open farm land. In the vicinity of Durham the valley narrows to a gorge.

The situation of Houghall is typical of much of the valley farm land in the north-east of England. On these river side 'haughs' (from the Anglo-Saxon 'healh', meaning 'flat land beside a river') occurs some of the best meadow and arable land in the district. This is particularly true of the Wear and Tyne valleys which are deeply entrenched over most of their courses. It is hoped that this study of the thermal properties of a typical example will illustrate the nature of the general conditions prevailing over these valuable areas.

Manley[3] has mentioned some of the unusual properties of the monthly mean and extreme temperatures at Houghall and he first drew attention to the relative continentality of its climate.

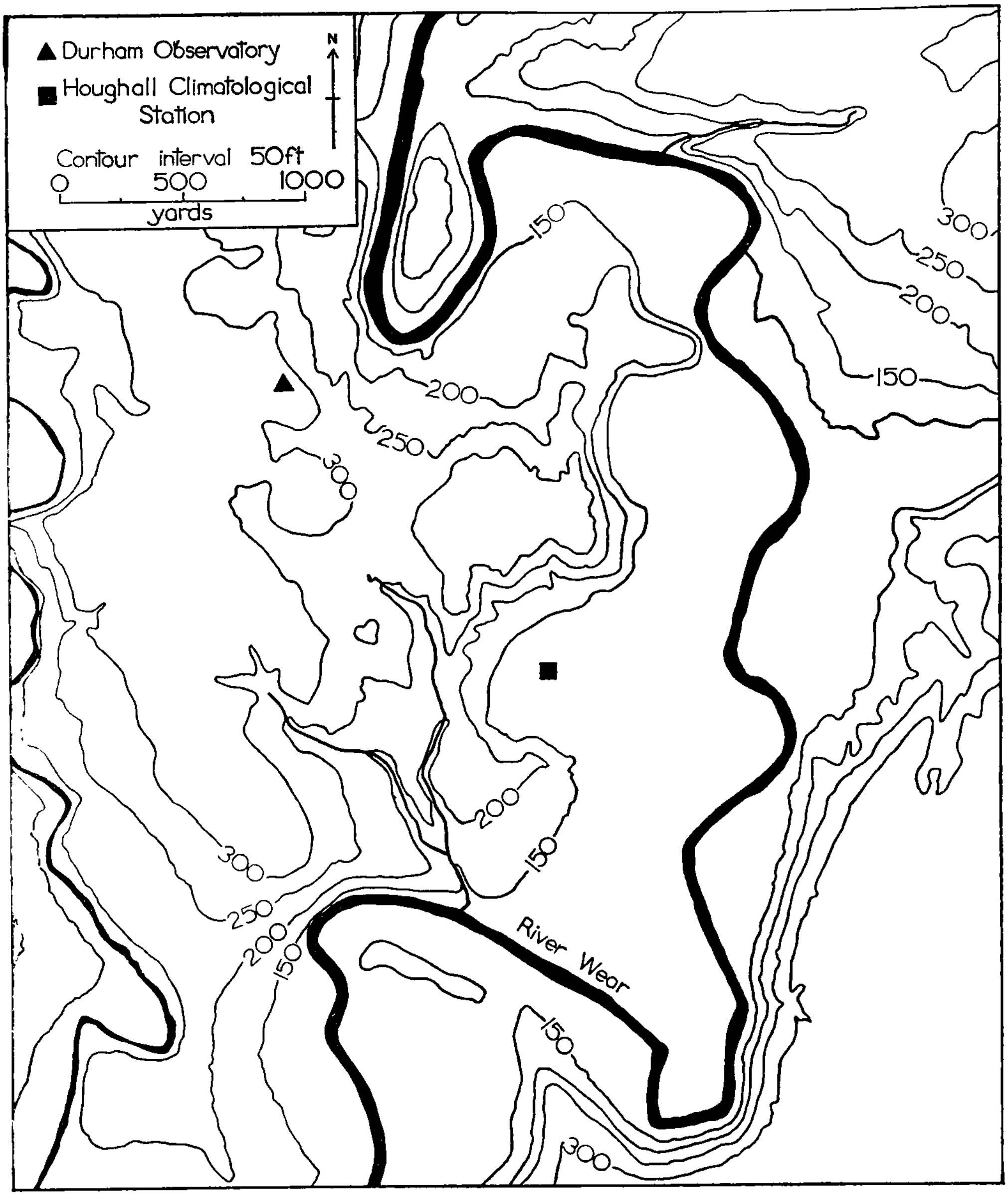

FIGURE I—RELIEF MAP SHOWING LOCATION OF HOUGHALL CLIMATOLOGICAL STATION AND DURHAM OBSERVATORY

The records.—The meteorological record at Durham Observatory is one of the oldest in the country, dating continuously from 1850. Observations were first made at Houghall in 1925. A twenty-year period, March 1925 to February 1945, is used in this comparison. This period was relatively mild over the country as a whole since it excludes the very cold decade 1885 to 1895. Consequently it is difficult to compare the absolute minima at Durham and Houghall during this period with the values from other stations since these are usually taken from different periods. Where necessary some comparisons are drawn from longer periods.

The daily screen and grass minimum temperatures have been used in this comparison.

Comparison of the daily screen minimum temperatures.—The monthly extreme screen minimum temperatures were lower at Houghall and the difference was greatest in winter (Table I).

TABLE I—EXTREME MONTHLY SCREEN MINIMUM TEMPERATURES (°F) 1925–45

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Houghall	—6	—1	8	18	21	28	32	32	26	19	16	10
Durham	3	11	15	22	24	30	34	35	30	22	20	18
Difference	9	12	7	4	3	2	2	3	4	3	4	8

Houghall is clearly subjected to particularly low extremes and this will be emphasized by a few random comparisons with other stations. Bilham[4] lists Houghall as being one of the twelve stations in the British Isles with a below-zero minimum screen temperature between 1895 and 1938. Eight of the remaining twelve stations were in Scotland. In March 1947 Houghall recorded a minimum screen temperature of —6°F which was 3°F colder than the previous March record for the British Isles. In 1959, a year taken at random, Houghall recorded more ground frosts than any other station reported in the *Annual Summary of the Daily Weather Report.* Only one other station came within 80 per cent of the Houghall total.

We now have an indication of the severity of the extreme conditions at Houghall; it remains to estimate the importance of these in the mean monthly and annual values.

The contrast between the mean monthly screen minimum temperatures at the two stations was smaller than that between the extreme monthly screen minima (Table II).

TABLE II—MEAN MONTHLY SCREEN MINIMUM TEMPERATURES (°F) 1925–45

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Houghall	30.8	32.0	33.7	37.0	40.4	46.4	50.5	50.0	45.8	40.4	35.5	32.5	39.5
Durham	32.0	32.7	34.2	37.2	41.0	46.5	50.9	50.5	46.5	41.2	36.7	33.8	40.3
Difference	1.2	0.7	0.5	0.2	0.6	0.1	0.4	0.5	0.7	0.8	1.2	1.3	0.8

These differences are surprisingly small. Standard-error testing proved significance of the difference only in January, September, October, November December and the mean annual values. The relatively small differences in February and March may be due to a higher frequency of wind frosts affecting both stations equally in those months. Later we shall find that the contrast between the grass minimum temperatures is also greatest in October, November and December. This may be partly caused by a more persistent snow cover providing insulation for the grass thermometer in the valley bottom in January and February. This would seem to happen on some cold nights when Durham has recorded grass minimum temperatures several degrees lower than those of Houghall during calm conditions.

The difference between the two sets of observations in Table II also seems to be reduced by the occasional occurrence of particularly warm nights at Houghall. Being higher and more exposed Durham will record lower minima than Houghall during periods of cold winds. Of course this contrast will be reduced by turbulent mixing. This greater range of minimum temperatures in the frost hollow can be seen in Figure 2 which shows the monthly frequency distributions of daily minimum temperatures at Houghall (Figure 2(*a*)), Durham (Figure 2(*b*)) and the percentage difference between these in Figure 2(*c*). In all months Houghall has a higher percentage of very high and very low minima but the contrast is greatest in winter and in the case of the low minima.

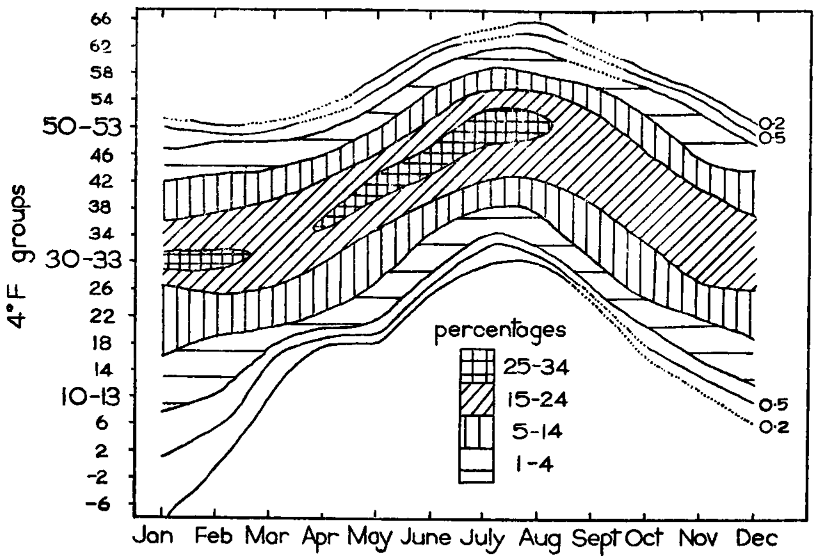

FIGURE 2(*a*)—MONTHLY FREQUENCY DISTRIBUTION OF SCREEN MINIMUM TEMPERATURES 1925–45 AT HOUGHALL

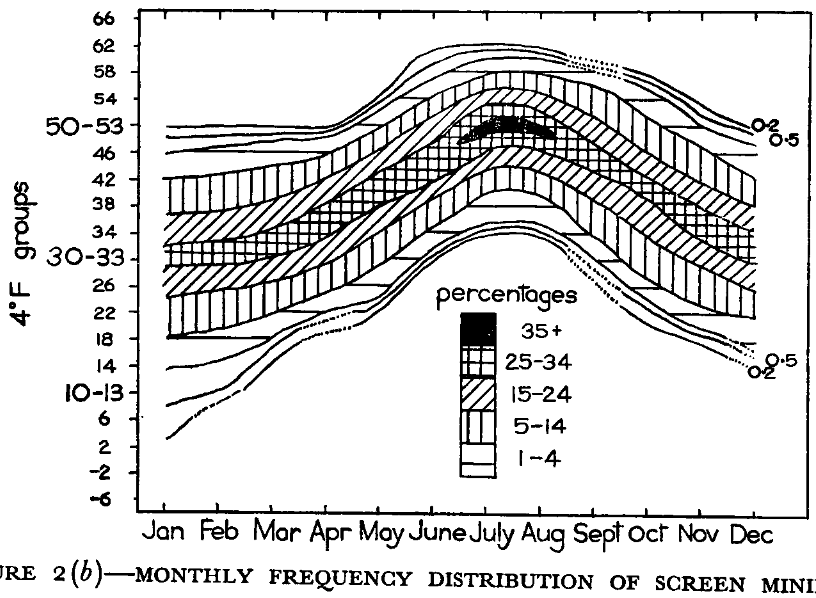

FIGURE 2(*b*)—MONTHLY FREQUENCY DISTRIBUTION OF SCREEN MINIMUM TEMPERATURES 1925–45 AT DURHAM

A numerical estimate of the greater variation in minimum temperatures in the frost hollow is contained in the curves of monthly standard deviation of daily minimum temperatures (Table III).

TABLE III—MONTHLY STANDARD DEVIATION OF DAILY SCREEN MINIMUM TEMPERATURES (°F) 1925–45

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Houghall	8.2	7·5	6·3	6.1	6.5	5·9	5·4	5·7	7·0	7·2	6.9	6.8	9.6
Durham	6.6	6.2	5·5	5·2	5·4	4·9	4·3	4·5	5·8	6.1	5·5	5·8	7·7

Now the greatest contrast is in January but November, October and September are again more severe than February, March and April respectively.

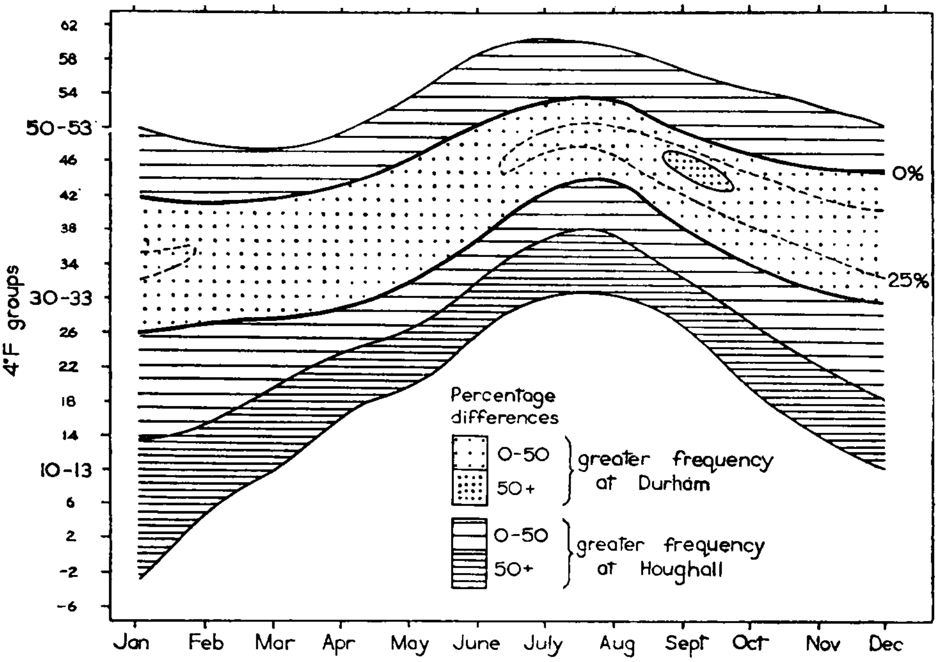

FIGURE 2(*c*)—PERCENTAGE DIFFERENCES BETWEEN FIGURES 2(*a*) AND 2(*b*)

The contrast between the frequencies of air frosts at Houghall and Durham also indicates relative severity in the valley bottom. The definition of an air frost is based on a screen minimum temperature of 32°F and below. Champion[5] has discussed the merits of the various definitions of ground frost in detail and favours an upper limit of 32°F. Hawke[1] and Hogg[6] also concern themselves with 'days with a minimum temperature of 32°F and below'.

TABLE IV—MEAN MONTHLY FREQUENCIES OF AIR FROSTS. 1925–45

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Houghall	17.5	14.4	12.7	6.7	4.1	0.6	<0.1	<0.1	1.2	4.7	10.5	15.2	87.7
Durham	15.9	13.3	11.5	5.7	2.6	<0.1	0.0	0.0	0.3	2.9	6.9	12.2	71.6

Houghall persistently suffers more air frosts than Durham especially in November and December. The total difference is not large, particularly when compared to other local contrasts based on altitude or distance from the sea. This will be illustrated with some examples given by Lewis.[7]

TABLE V—SEASONAL FREQUENCIES OF AIR FROSTS (DAILY SCREEN MINIMUM TEMPERATURE 32°F OR BELOW)

	Spring (Mar. Apr. May)	Summer	Autumn	Winter
Houghall	23.5	0.7	16.4	47.1
Durham	20.0	<0.1	10.1	41.6
Tynemouth*	6.1	0.0	2.9	14.9
Dun Fell* (north Pennines)	60	1	29	78
Cockle Park* (Northumberland)	20.4	<0	9.7	39.7

* after Lewis.

The mean annual number of days with air frost at Houghall is only 64 per cent of the Rickmansworth value. The relatively small contrast between Houghall and Durham in Table V may be partly due to the fact that it ignores the severity of the frosts. In fact a greater difference between the two emerges when we consider the mean monthly day-degrees of frost.

Perhaps the greater percentage differences in the summer half year are due to the likelihood that very low minimum temperatures at that time are more usually caused by nocturnal radiation than is the case in winter. Table VI also shows that the greatest winter contrasts are in October, November and December, although these months are not as severe as January, February and March in absolute terms.

TABLE VI—MEAN MONTHLY DAY-DEGREES BELOW 32°F (SCREEN MINIMUM) 1925–45

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Houghall	111.0	78.8	55.0	24.5	13.4	0.5	0.0	0.0	2.5	15.5	40.5	74.5	421
Durham	78.5	57.5	38.2	12.7	5.1	0.1	0.0	0.0	0.3	6.6	22.5	45.1	267
Durham as a percentage of Houghall	71	73	70	52	38	20	—	—	10	43	53	61	63

Comparison of the daily grass minimum temperatures.—For the sake of brevity the daily difference in grass minimum temperature between Houghall and Durham will be termed d*T*. Positive d*T* refers to higher grass minima at Durham.

The extreme monthly grass minima are given in the following table.

TABLE VII—EXTREME MONTHLY GRASS MINIMUM TEMPERATURES (°F) 1925–45

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Houghall	—11	—7	4	11	12	20	26	26	20	15	9	5
Durham	—2	2	7	14	16	23	26	28	24	15	12	12

Except in January, February and December these differences are rather small. October is particularly surprising in this respect in view of the considerable contrasts experienced in that month in the case of the air minima. Ground frosts have occurred at both stations in all months. Later we shall find however that, with the exception of January and February the extreme minima at Houghall are considerably higher than those at Rickmansworth.

TABLE VIII—MEAN MONTHLY VALUES OF d*T* (°F) 1925–45

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
3.2	2.7	2.5	2.0	1.3	0.5	0.8	1.5	2.0	3.3	3.5	3.5	2.2

All of these differences are 'positive'. The mean monthly grass minima are consistently lower in the frost hollow. November and December are again particularly severe months in the frost hollow. Since grass minimum temperatures represent extremes it is not surprising to find that the differences indicated in Table VIII are greater than those in Table II.

There is a tendency for a greater range of d*T* in winter than in summer. In Figure 3 the frequency distributions of d*T* for the winter and summer half years have been plotted as continuous curves. The simplification of the temperature scale was intended to smooth the minor irregularities. There is a lag of approximately 2 °F between the two curves. This lag may give an indication of the greater severity of winter conditions in the frost hollow compared with those of summer. Only 13 per cent of the winter values of d*T* occurred at the mode in Figure 3 compared with 16.5 per cent in summer. This is not a large difference but it indicates a greater range of values in winter which agrees with the results on air minima shown in Figure 2.

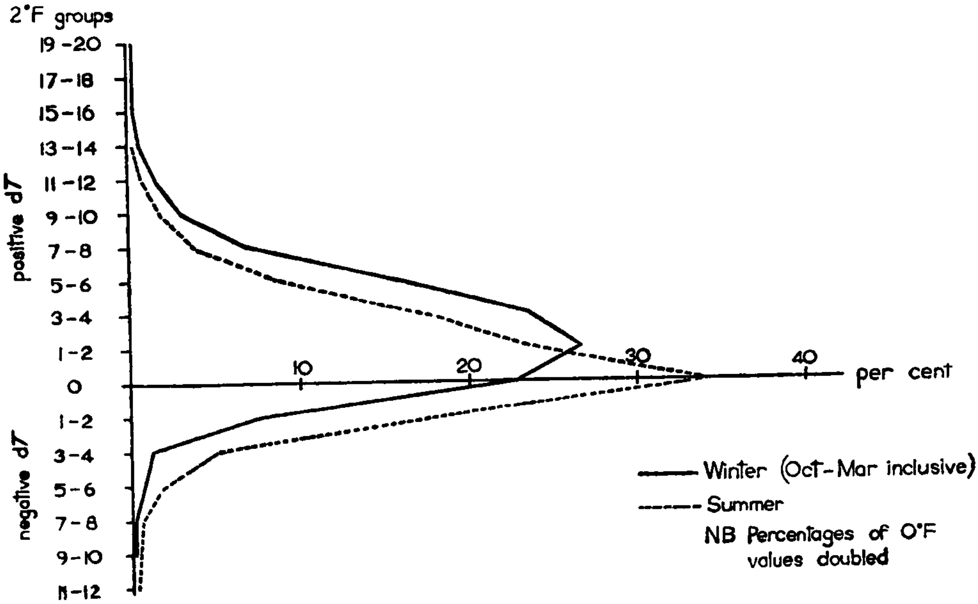

FIGURE 3—PERCENTAGE FREQUENCY DISTRIBUTIONS OF dT 1925–45

In Figure 4 the percentage frequency distributions of dT for selected periods are compared with the percentage mean annual frequencies. Winter is outstanding mainly for its high percentage of large positive values of dT. In winter there are a large number of occasions when the grass minima at Houghall are considerably lower than those at Durham. The opposite applies in summer and there is a high frequency of relatively high grass minima at Houghall. In Figure 4C this contrast between winter and summer is seen to be magnified when January and July, the two extreme months, are compared. The transitional features of April and September are shown in Figure 4A.

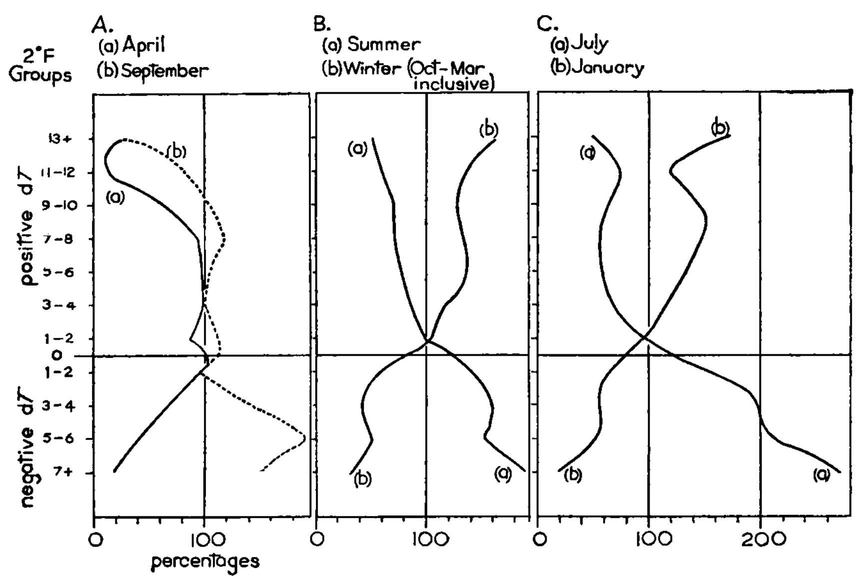

FIGURE 4—PERCENTAGE RATIO BETWEEN FREQUENCY DISTRIBUTION OF dT FOR SELECTED PERIODS AND MEAN ANNUAL VALUES, 1925–45

A limit of 32°F and below will be used to define a ground frost. The frequencies of ground frost are given in the following table.

TABLE IX—MEAN MONTHLY FREQUENCIES OF GROUND FROSTS 1925–45

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Houghall	24.5	22.7	21.6	15.7	10.0	3.7	0.7	1.0	6.0	13.2	19.2	22.6	162
Durham	18.5	18.0	17.5	12.2	7.5	2.9	0.7	0.9	3.4	8.2	13.4	16.9	119

The contrast between the stations when ground frosts are considered is greater than in the case of air frosts. Taking the year as a whole Durham has only 74 per cent of the number of ground frosts which Houghall has, while the equivalent percentage for air frosts is 82. We would expect this to be so since ground observations are more indicative of extremes than air observations. Again we find a greater contrast between the stations when the severity of the ground frosts is considered. While Houghall has only 33 per cent more ground frosts per year than Durham the number of day-degrees below 32°F at the former amounts to 66 per cent more than the Durham value.

General conclusions and some comparisons with Rickmansworth.— By local standards the thermal properties of the Wear Valley bottom are continental. Mean minimum temperatures are relatively low and are subject to greater variation in the frost hollow as compared to conditions on the neighbouring plateau surface. These contrasts apply particularly in early winter. October, November and December are months of greater relative coldness in the frost hollow although in absolute terms the most severe conditions prevail in January, February and March.

In comparison with conditions at Rickmansworth Houghall cannot rank as a severe frost hollow. The monthly mean screen minimum temperatures at Houghall are considerably higher than those at Rickmansworth. The difference between the two amounts to a maximum of 5.1°F in September and a minimum of 2.2°F in May and June. The mean annual difference is 3.1°F. These lower means at Rickmansworth may be partly due to the fact that the two records are not drawn from the same period, but the cold year of 1929 is only included in the Houghall record.

The extreme minimum screen temperatures at Rickmansworth were lower than those at Houghall except in January, February and September. The same is true of the grass minimum temperature extremes with the exception of the September value which was lower at Rickmansworth.

The mean monthly frequencies of air and ground frosts were generally higher at Rickmansworth than at Houghall. In April, September and October Rickmansworth has over twice as many days with air frosts as Houghall. Taking the year as a whole Houghall has only 64 per cent as many air frosts as Rickmansworth. There is a smaller contrast when ground frosts are considered and Houghall has 80 per cent as many days with ground frost as Rickmansworth.

The precise reasons for the greater severity at Rickmansworth are not known. Certainly the opportunities for katabatic drainage on a 'regional' scale are better in the Chiltern dip-slope valleys than in a widely meandering valley like that of the Wear (Heywood)[8]. The most striking differences exist between Houghall and Rickmansworth when means are considered. Perhaps this is due to the occasional relatively high minimum temperatures at Houghall. It is likely that the more deeply entrenched Wear Valley will provide greater shelter than the Chess during periods of cold, windy weather. If this is so it would tend to elevate the mean minima at Houghall with respect to those at Rickmansworth. The gravel soils of the Chess Valley would also tend to produce lower minima than the heavier silts and clays of the Wear Valley.

It would appear from this evidence that the farmer in the northern frost hollow will only occasionally be subjected to the severe conditions which are rather more commonplace to his southern counterpart at Rickmansworth.

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REVIEWS

Meteorologie der Strahlströme (*Jet Streams*), by E. R. Reiter. 10 in. x 7 in. pp. xi + 473, *illus.*, Springer-Verlag, Wien 1, Mölkerbastei 5, 1961, Price: £12.

A great deal has been written about the jet stream since evidence of this feature of atmospheric flow was first uncovered and studied in detail shortly after the end of World War II. Nevertheless, it is at first sight somewhat surprising to find an entire textbook of over 400 pages devoted to this one phenomenon.

Yet at close quarters it is soon realized that this work is no ordinary discourse on the jet stream alone. It constitutes, in effect, a comprehensive treatment of the dynamics of atmospheric motion, with the jet stream providing the motif behind the presentation of the work as a whole.

The jet stream is indeed a crucial fact of our planetary atmosphere. It can be used as a practical example to be related in one way or another to many facets of theoretical dynamic meteorology, in addition to synoptic meteorology and general circulation climatology. A treatise on the jet is therefore by nature a study of these three basic disciplines of meteorological science.

If anything the book is almost too thorough touching as it does upon the various methods of measuring winds, and discussing at some length the errors and variations which may occur in wind measurement. Long passages of the text are printed in smaller type so that they can be identified by the reader and omitted on first reading if desired. The material is up to date including the results derived from the famous "Project Jet Stream" aircraft runs across jet stream cores, about which Dr. Reiter has written in the research journals.

The book is costly but extremely well produced and profusely illustrated with excellent and informative diagrams. It is a classic of its kind and should be read by students and research workers in meteorology and others concerned with atmospheric motion or fluid dynamics. There are some sixty pages of references which constitute a very useful bibliography of the literature on the subject.

A. H. GORDON

PUBLICATION RECEIVED

Meteorological Memoirs. Vol. I, Meteorological Department, Republic of Iraq. 11 in. x 8½ in., pp. (ii) + 165, *illus.*, Directorate General of Civil Aviation, Meteorological Department, Ministry of Communications, Republic of Iraq, 1962.

This is the first volume of a new series. It comprises 15 scientific papers by Iraqi meteorologists, covering many aspects of the meteorology of Iraq.

Aeronautical descriptive climatological memoranda, Federal Meteorological Department, Rhodesia and Nyasaland. 12½ in. x 7¾ in., pp. 15, *illus.*, Ministry of Transport, Salisbury, Rhodesia, 1961.

OFFICIAL PUBLICATIONS

The following publications have recently been issued:

SCIENTIFIC PAPERS

No. 16—*An experiment in operational numerical weather prediction*, by E. Knighting, B.Sc., G. A. Corby, B.Sc. and P. R.Rowntree, B.A.

The paper describes an operational experiment in numerical weather forecasting carried out within the Meteorological Office from November 1960 to June 1961 using the electronic computer METEOR. Initial data for 0001 GMT were analysed objectively within the computer for three levels in the atmosphere and forecasts based on these data were computed for 0600 GMT on the following days. A novel feature of the experiment was that the forecast computation was interrupted to allow the inclusion of such 0600 GMT data as were available at the appropriate stage in the calculation. Statistical measures of the accuracy of the forecasts are given together with several examples of the computed forecasts.

No. 17—*Extremes of wind shear*, by A. F. Crossley, M.A.

Values of large horizontal and vertical shear are gathered from a survey of appropriate publications and are discussed with reference to the distance over which each is sustained. In the vertical, curves of extreme shear are estimated for north-west Europe and for the U.S.A. Use is made of recordings of the Crawley automatic radar theodolite over a period of 12 months; these are analysed to obtain frequency levels of shear over various height intervals up to 10,000 feet, and a method is described for estimating corresponding long-term frequencies for other places, in particular for New York. In the horizontal, the data have been applied to obtain a curve of extreme shears in relation to distance over which they are measured. There is some discussion of anticyclonic shear with reference to stability criteria; although several instances are noted of anticyclonic shear apparently greater than the Coriolis parameter, in no case is the excess beyond the range of possible observational errors.

GEOPHYSICAL MEMOIR

No. 106—*A meso-synoptic analysis of the thunderstorms on* 28 *August* 1958, by D. E. Pedgley, B.Sc.

This Memoir describes the structure and evolution of some particularly well defined medium-scale anticyclones and depressions (with diameters of 50 to 100 miles) which accompanied the widespread thunderstorms over England on 28 August 1958. These meso-scale features closely resembled those observed in other countries, notably the U.S.A. and Japan. Sufficient data were available to construct a "model" thunderstorm meso-system, and the physical processes involved in its life-cycle are discussed. The specialized techniques of analysis used show that considerably more detail can be deduced from data available as routine than is currently obtained by day-to-day synoptic weather analysis.

LETTER TO THE EDITOR

Analysis of forecasting in the Mediterranean

Mr. Kirk, in his very clear and interesting article "Analysis of a weak discontinuity at Malta, 2 September 1960" published in the *Meteorological Magazine* of February 1963, emphasizes the serious limitations of the surface synoptic chart as an aid to analysis in the Mediterranean. As long ago as 1950, I wrote an article "Upper frontal analysis in the Mediterranean", (*Meteorological Magazine* 1950) in which I drew attention to the value of upper air charts, in particular the 850 millibar chart, for the purpose of analysis and forecasting. However, to judge from my experience as a Senior Forecaster at London (Heathrow) Airport during the years 1955–59, I very much doubt whether, with the exception of those forecasters who have actually worked at Luqa, the importance of the 850 mb chart and other upper air charts as analysis and forecasting tools in the Mediterranean, is even yet fully appreciated. As Mr. Kirk points out, few examples are available to illustrate the nature of the difficulties of analysis in the Mediterranean area. I therefore warmly welcome this article, strongly recommend it for careful study by all meteorologists who are liable to be concerned with forecasting in the Mediterranean, and hope it will be followed from time to time by further instructive examples.

Meteorological Office, Bracknell. F. E. LUMB

OBITUARY

Mr. Percy Powell.—It is with deep regret that we have to report that Mr. Percy Powell, "Pip" to all his friends and associates, died on 1 February 1963. When driving home after morning duty he was in collision with a coach, and sustained fatal, though mercifully instantaneous, injuries.

Mr. Powell who was 61 when he died, entered the Meteorological Office in 1919 as a Boy Clerk and spent the next seven years in the Forecast Division, being promoted Technical Assistant in 1922 and then regraded as a Grade III Clerk in 1923. In the years before the war he served at several stations (Cardington, Lympne, M.O.2 again, Andover and Wyton) being assimilated as Assistant Grade III in 1935 then promoted to Grade II in 1938.

He was mobilised at the outbreak of war and served for a time with No. 2 Group in France returning to this country to serve both as a civilian and as a Flight Lieutenant in the R.A.F.V.R. at a number of formations. After his release from the R.A.F.V.R. in 1945, and assimilation as Experimental Officer in 1946, he served first at H.Q. No. 3 Group and was then posted to Germany where he was promoted to Senior Experimental Officer in 1949. Returning to England in 1952 he spent the rest of his life at H.Q. No. 3 Group Mildenhall, retiring in 1962 but being re-employed as a Disestablished Experimental Officer.

During his last few years Mr. Powell did much work as the Regional Representative of the I.P.C.S.

"Pip" was a most kindly, friendly and helpful man. His colleagues at Mildenhall had much respect and affection for him, and the R.A.F. were always very happy to receive his sound level-headed advice. He will be mourned by his many friends throughout the Office and elsewhere.

Deep sympathy is extended to his widow and family in their great sorrow.

D. W. J.

CORRIGENDA

Under the heading at the top of p. 310 of the November 1962 *Meteorological Magazine*, 1957 to 1961 should read 1959 to 1961.

On the front cover of the February 1963 *Meteorological Magazine*, No. 1086 should read No. 1087.

METEOROLOGICAL OFFICE M.O. 738

THE METEOROLOGICAL MAGAZINE

Vol. 92, No. 1090, May, 1963

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A 'PRESSURE JUMP' AT MALTA—1 JUNE 1961

By T. H. KIRK

Reference has already been made to the occurrence of 'pressure jumps' at Malta.[1] The present note provides the synoptic background to a particularly good example. All times are in GMT except where otherwise stated.

Figures 1 to 4 show the synoptic situation at the surface at 0001 on 31 May, and 0001, 0600 and 1200 on 1 June. At 0001 on 31 May, a trough of low pressure was evident in the extreme western Mediterranean, associated with a depression over north-west Spain. Pressure was almost uniform over the

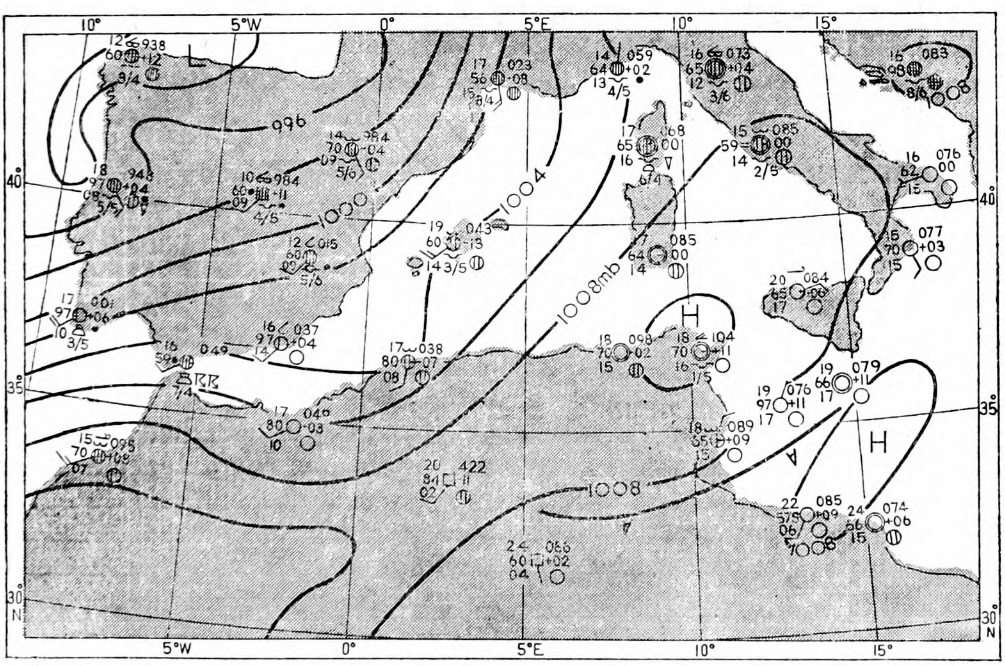

FIGURE 1—SURFACE CHART FOR 0001 GMT, 31 MAY 1961

A———*A* advection discontinuity

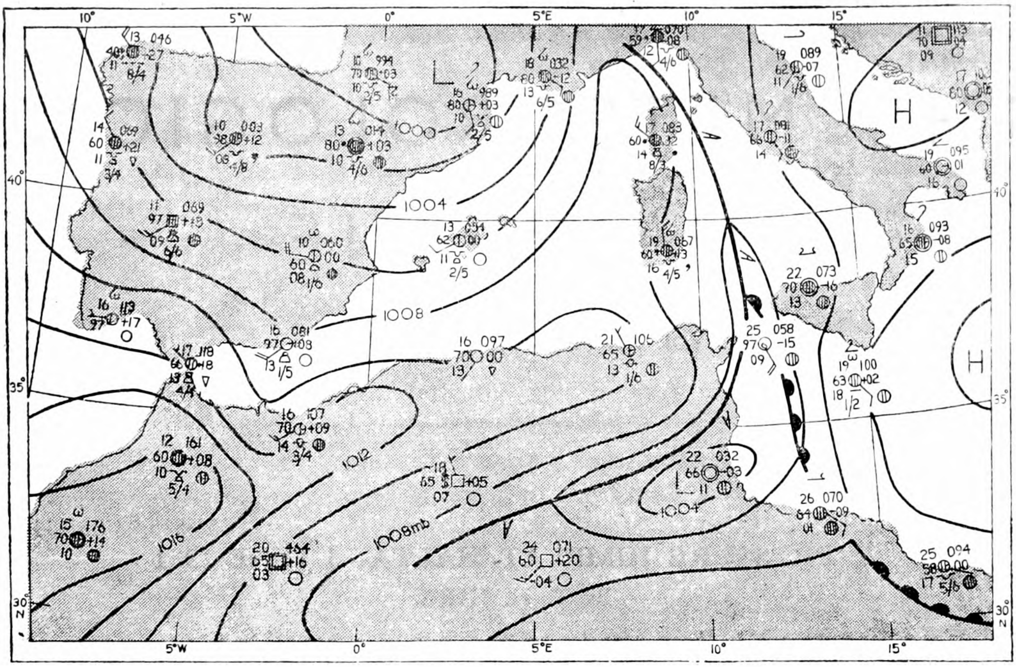

FIGURE 2—SURFACE CHART FOR 0001 GMT, 1 JUNE 1961
A———*A* advection discontinuity

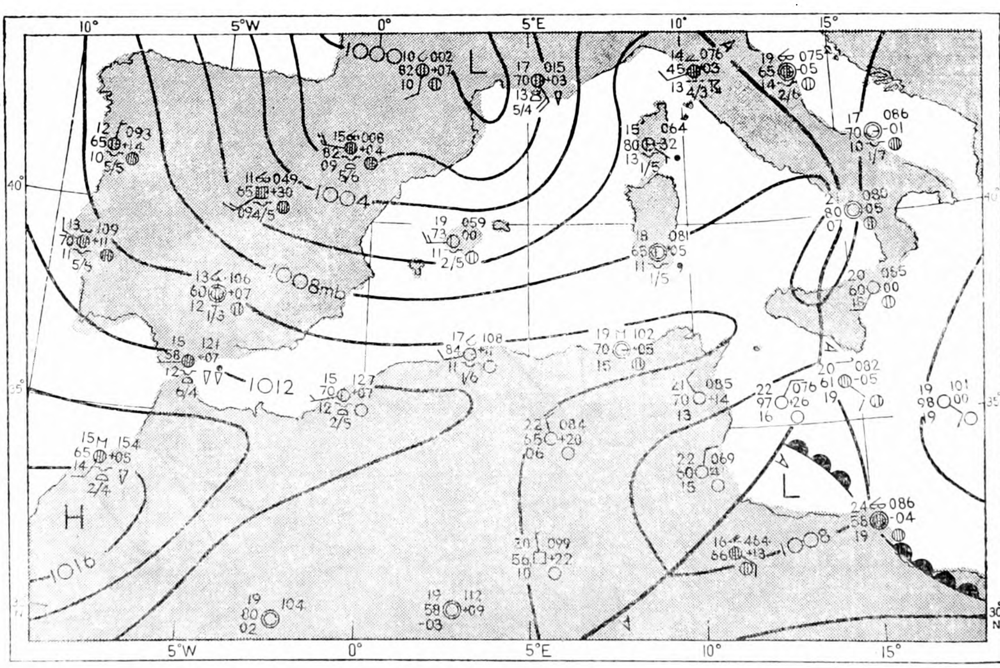

FIGURE 3—SURFACE CHART FOR 0600 GMT, 1 JUNE 1961
A———*A* advection discontinuity

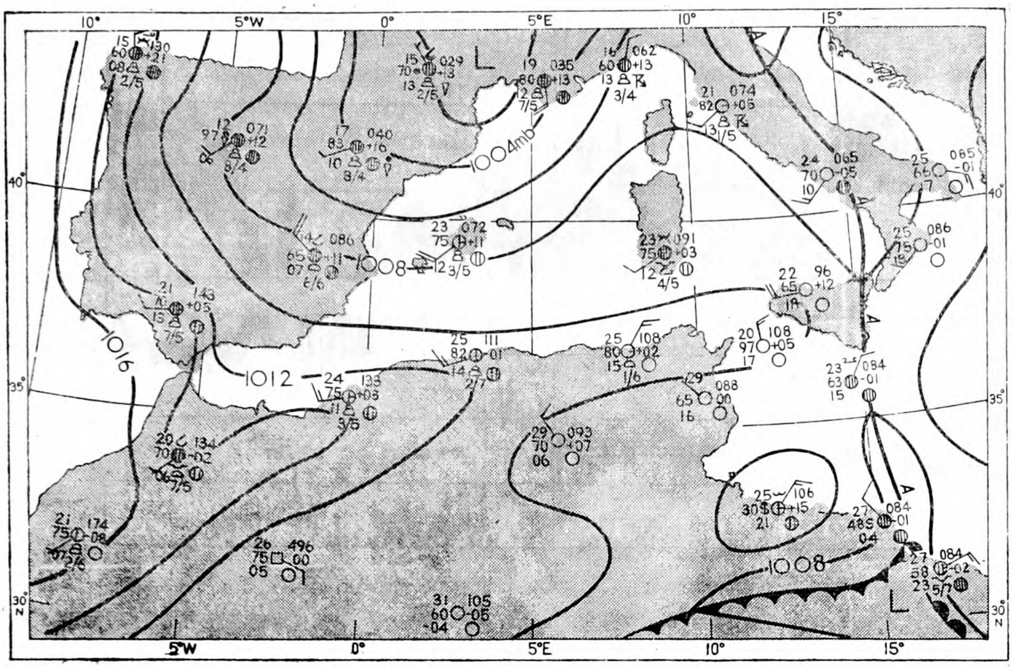

FIGURE 4—SURFACE CHART FOR 1200 GMT, 1 JUNE 1961

A———*A* advection discontinuity

remainder of the Mediterranean. There was a steady eastward motion of this trough accompanied by the formation of a minor secondary depression over eastern Algeria at 1800. At 0001 on 1 June, the main trough extended from east of Corsica to west of Pantelleria and thence south and south-west, the separate centre being no longer in evidence, presumably due to lack of data. At 0600 there is clear evidence of a separate centre to the south-west of Malta with a sharp trough extending from this position to west of Malta, to east of Palermo and thence to east of Rome. It is the passage of this sharp trough which is of interest.

Figure 5 shows the sequence of events at Malta recorded by the autographic instruments on 1 June 1961. A 'pressure jump' occurred at about 0825 local time (GMT + 1 hour) accompanied by marked oscillations of the wind direction. The register of observations at Luqa shows that the pressure rose by 1.7 mb between 0715 and 0745 which confirms the barogram trace. At this time the sky was overcast with cirrostratus, and one-eighth of stratus at 800 feet at 0715 was replaced by one-eighth of stratocumulus at 1200 feet at 0745. The thermogram shows a distinct and abrupt change in the rate of rise of temperature at this time and the hygrogram a sharp and somewhat uneven fall until, at about 1000 local time, when the wind had settled down again very close to its former direction, the humidity decreased to 49 per cent and remained at this figure with only minor variations until 1240 local time. The anemogram shows not only marked variations of wind direction at the passage of the 'jump' but also the very sharp drop in speed which is as characteristic for the anemogram as the sharp pressure rise is for the barogram. On all records, after the passage of the 'jump', there is evidence of small oscillations suggesting wave motion.

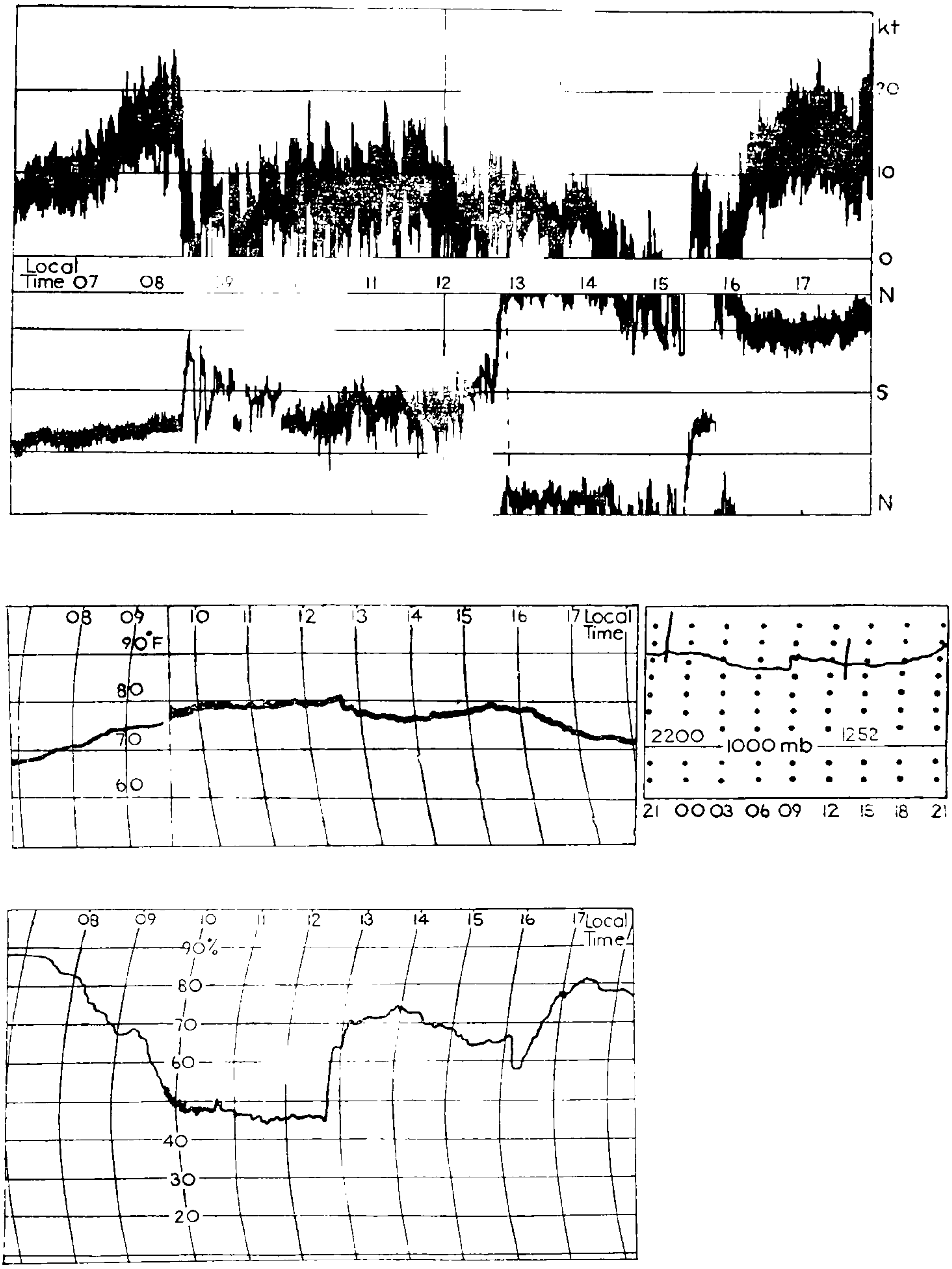

FIGURE 5—PASSAGE OF PRESSURE JUMP AND FRONT AT MALTA, 1 JUNE 1961
Time of pressure jump 0825 approximately, time of front 1240 approximately.
All times are local (GMT + 1 hour).

Anemogram — top chart

Thermogram — middle left

Barogram — middle right

Hygrogram — bottom chart

The next discontinuity, marked *A*———*A* in Figures 1 to 4, 9 to 11, 13 and 14, occurred at approximately 1240 local time, a sharp veer of wind being accompanied by a marked temperature fall of more than 3°F and an accompanying sharp rise of relative humidity to 64 per cent. There was no apparent change in the barogram trace. Except for the lack of barometric evidence this discontinuity had the characteristics of a surface cold front. It is evident that the sequence of events clearly shows two discontinuities in the passage of this trough, first the 'pressure jump' and then the surface cold 'front'.

Before discussing this aspect further it may be profitable to examine the available upper air data. Figures 6 to 8 give the successive upper air ascents at

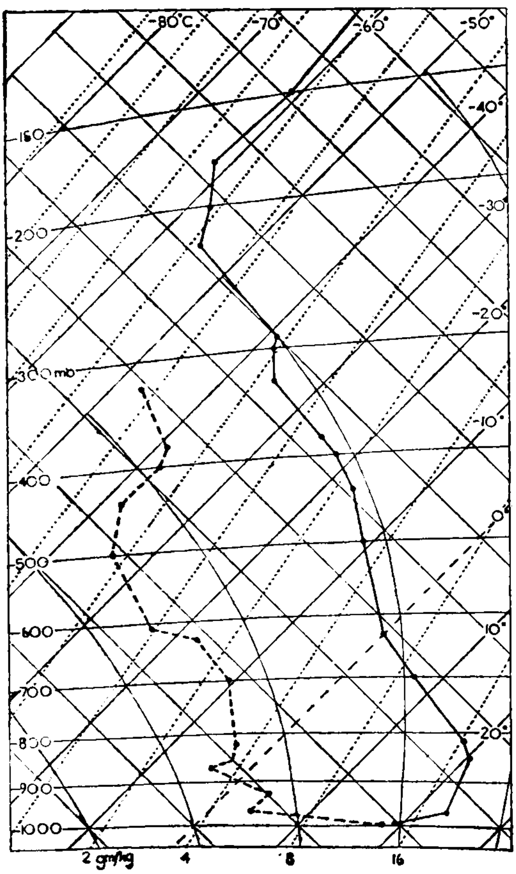

FIGURE 6—TEPHIGRAM FOR MALTA 0001 GMT, 1 JUNE 1961

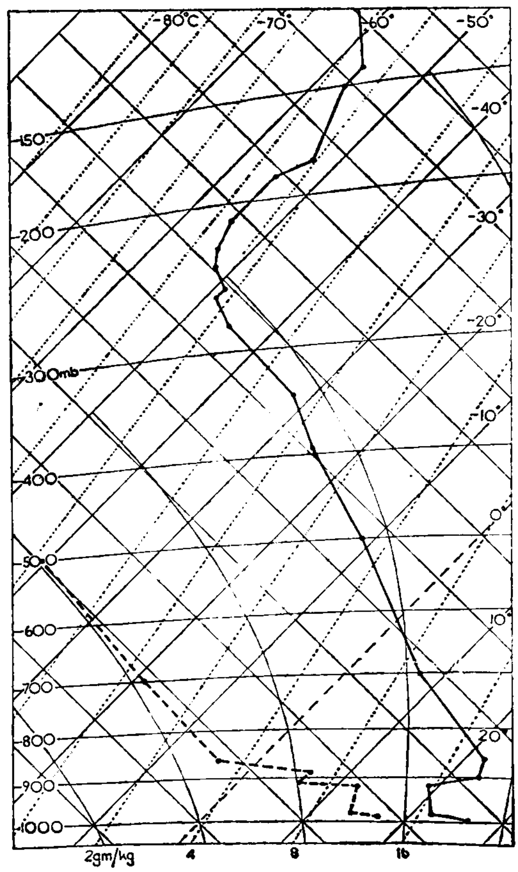

FIGURE 7—TEPHIGRAM FOR MALTA 1200 GMT, 1 JUNE 1961

——— dry-bulb temperature, - - - - dew-point temperature

Qrendi, Malta. The start of the midday ascent on the 1st was at 1130 when the surface 'front' was just passing Qrendi. It is seen that the base of the inversion, which at 0001 was at the surface, has been lifted to 890 mb. It is not possible to decide whether this was due to the 'pressure jump' or to the initial stage of the surface 'front'; nor can the sharp drop in the height of the tropopause from 177 mb to 211 mb strictly be attributed to one or the other discontinuity. It is noted, however, that at most of the lower levels the main temperature fall occurred after 1200 as shown by the subsequent ascents at 0001 and 1200 on the 2nd. The synoptic sequence is given by Figures 9 to 23 at the various levels: 850, 700, 500, 300 and 200 mb.

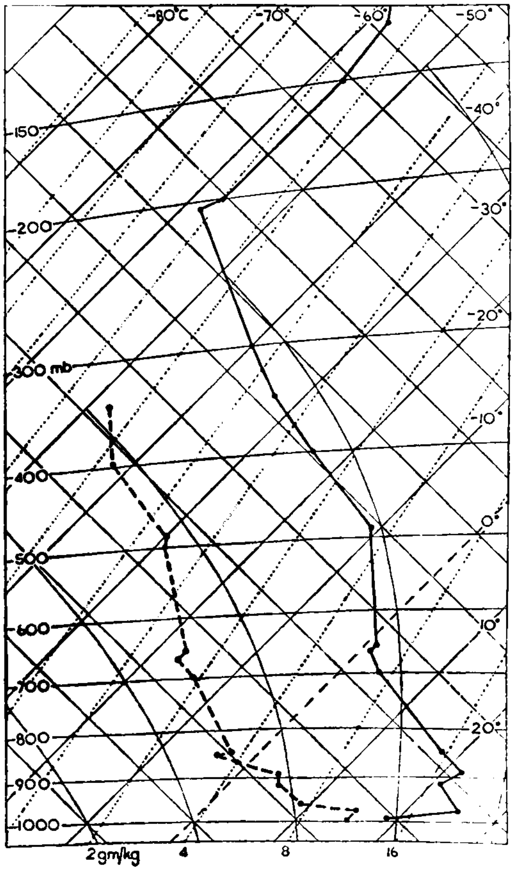

FIGURE 8—TEPHIGRAM FOR MALTA 0001 GMT, 2 JUNE 1961

——— dry-bulb temperature, - - - - dew-point temperature

850 *mb*, *Figures* 9–11.—At 0001 31 May, the trough in the western Mediterranean was associated with a warm thermal ridge and a tight thermal field extended from eastern Algeria to Greece. At 0001 1 June, a sharp trough had developed behind the position of the surface discontinuity. This is supported by the winds at both Elmas and Marseilles. The wind at Tunis, however, suggests that if this sharp trough existed in this latitude it would be situated somewhere between this station and Pantelleria. At 1200 the advection discontinuity *A*———*A* had just passed Malta and the main trough in the contour field appeared to be still to the west. The temperature at Malta increased from 20°C at 0001 to 21°C at 1200 then fell to 18°C at 0001 on the 2nd and further to 14°C by 1200.

700 *mb*, *Figures* 12–14.—At 0001 31 May, the main trough in the contour field was over south-west Spain and Morocco and a thermal ridge extended from Tunisia to north-west Spain and southern France. At 0001 1 June, a sharp trough is seen in the contour field just south-west of Sardinia, and strong warm air advection is in evidence not only ahead of the thermal ridge but also at Elmas and Marseilles. The slight cold advection along the Algerian coast suggests the possibility of frontogenetic action in the trough behind the discontinuity as marked.

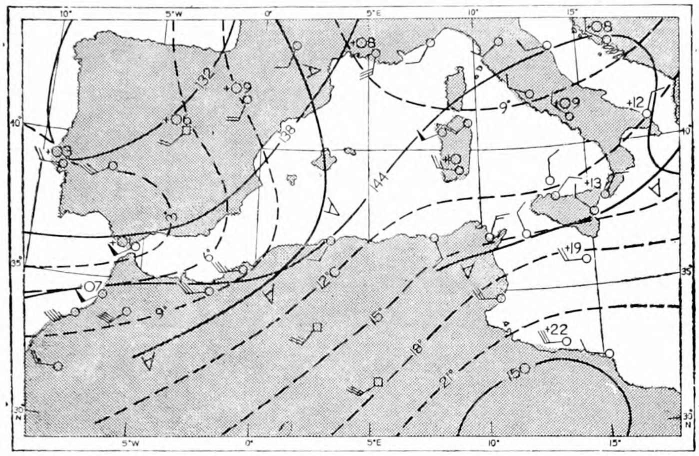

FIGURE 9—850 MB CHART FOR 0001 GMT, 31 MAY 1961
——— contours in geopotential decametres
A———*A* advection discontinuity, – – – – isotherms

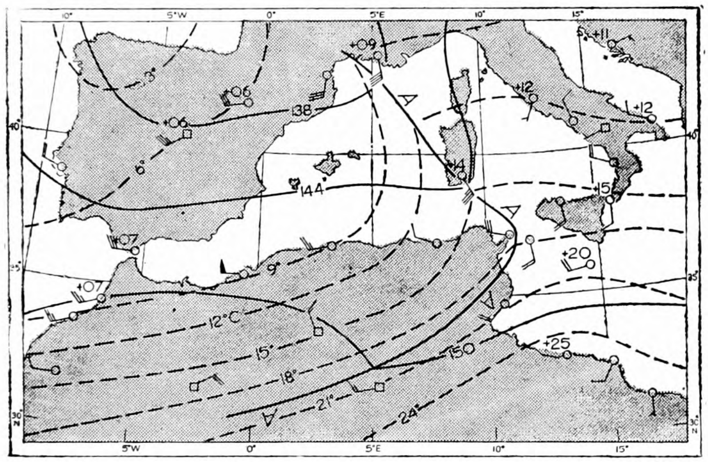

FIGURE 10—850 MB CHART FOR 0001 GMT, 1 JUNE 1961
——— contours in geopotential decametres
A———*A* advection discontinuity, – – – – isotherms

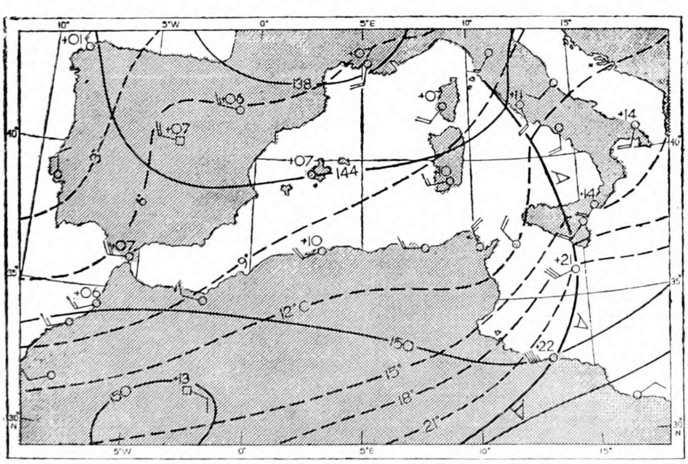

FIGURE 11—850 MB CHART FOR 1200 GMT, 1 JUNE 1961
——— contours in geopotential decametres
A———*A* advection discontinuity, – – – – isotherms

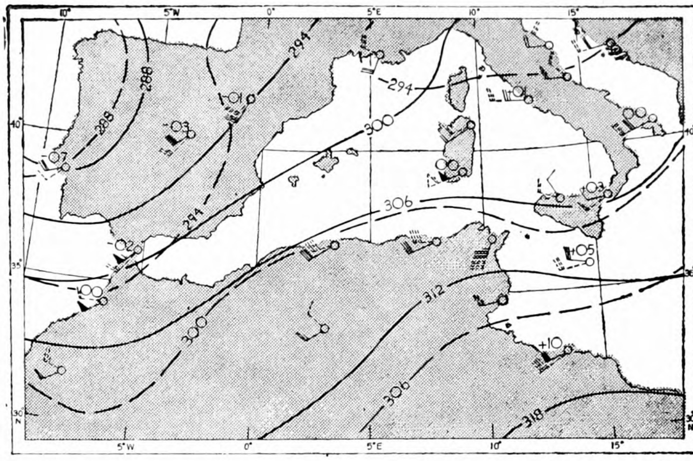

FIGURE 12—700 MB CHART FOR 0001 GMT, 31 MAY 1961
——— contours, —— —— 1000–700 mb thickness, in geopotential decametres

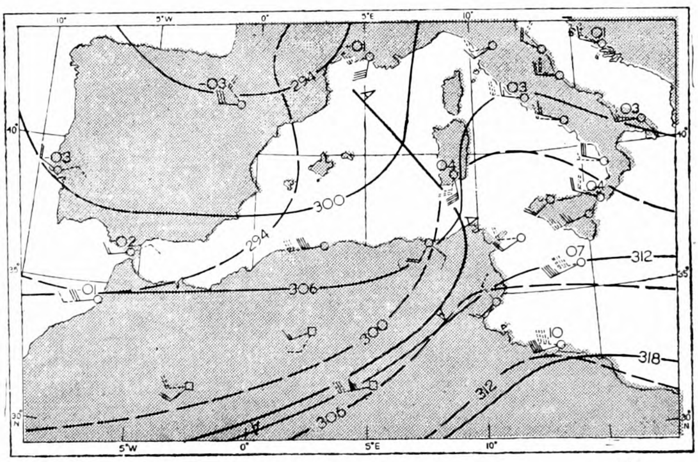

FIGURE 13—700 MB CHART FOR 0001 GMT, 1 JUNE 1961
——— contours, —— —— 1000–700 mb thickness, in geopotential decametres
A——A advection discontinuity

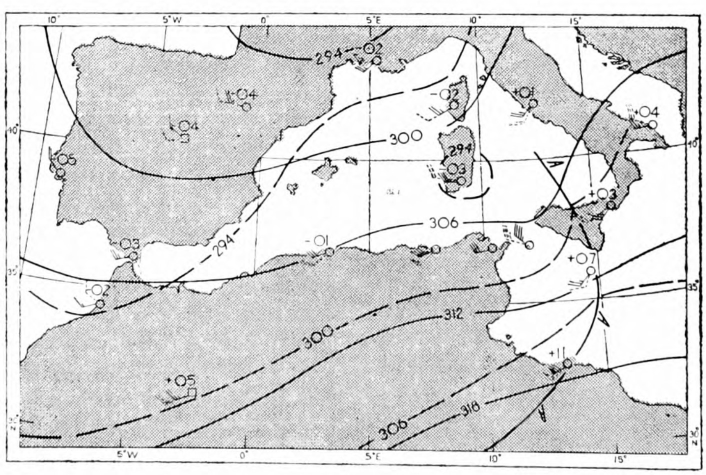

FIGURE 14—700 MB CHART FOR 1200 GMT, 1 JUNE 1961
——— contours, —— —— 1000–700 mb thickness, in geopotential decametres
A——A advection discontinuity

At 1200 the cold advection indicated by the wind field at Malta and Idris suggests that the discontinuity should be placed through these stations leaving a trough in the contour pattern behind. As yet, however, there had been no decrease in the temperatures at these places. By 0001 2 June, the temperature at Malta had decreased from 7°C to 4°C and that at Idris from 11°C to 7°C.

500 *mb*, *Figures* 15–17.—At 0001 31 May, the trough in the contour pattern was situated west of the Straits of Gibraltar and a south-west to west flow prevailed over the whole Mediterranean. By 0001 1 June, the surface discontinuity appeared to be associated with a minor thermal trough at 500 mb. Cold advection was occurring ahead of it and strong warm advection behind it. At 1200 this thermal trough appeared to have run ahead of the discontinuity and its passage through Malta might well have corresponded with the pressure jump ahead of the surface discontinuity.

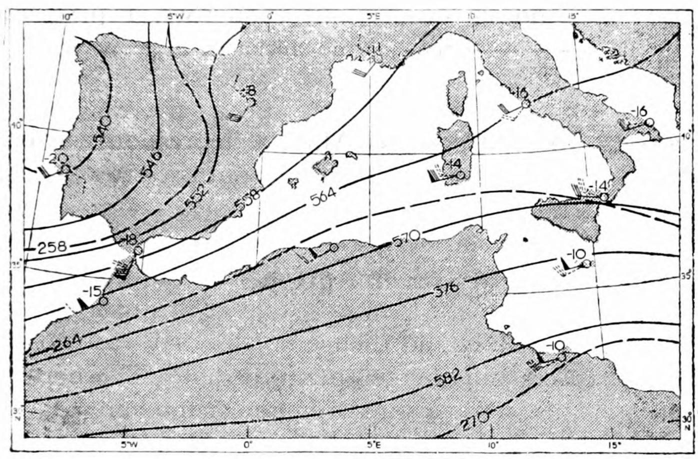

FIGURE 15—500 MB CHART FOR 0001 GMT, 31 MAY 1961
——— contours, —— —— 700–500 mb thickness, in geopotential decametres

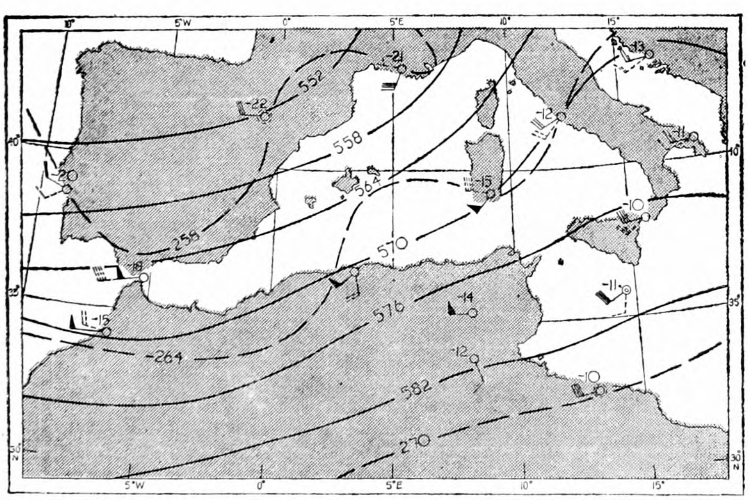

FIGURE 16—500 MB CHART FOR 0001 GMT, 1 JUNE 1961
——— contours, —— —— 700–500 mb thickness, in geopotential decametres

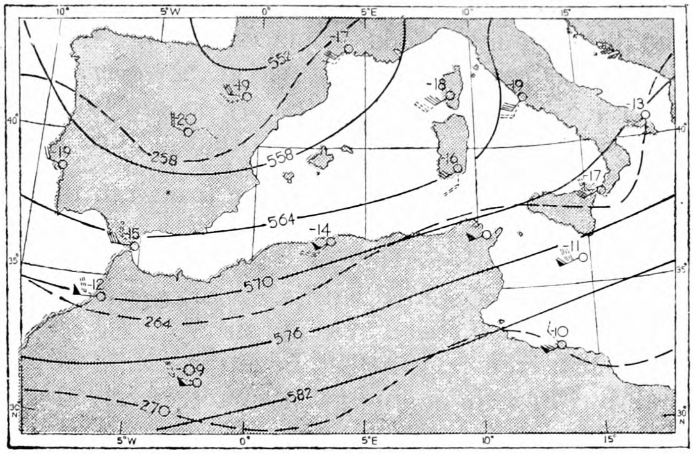

FIGURE 17—500 MB CHART FOR 1200 GMT, 1 JUNE 1961
——— contours, —— —— 700–500 mb thickness, in geopotential decametres

300 *mb*, *Figures* 18–20.—At 0001 31 May, a depression was centred west of Portugal with an associated trough extending south-westwards. A strong flow, in wave pattern, extended over the Mediterranean with a jet stream from northern Spain to extreme southern Italy to Greece and Turkey. By 0001 1 June, a strong south-west to west flow prevailed from the Straits of Gibraltar to Malta and Tripoli. The main thermal ridge at this time extended from the Sea of Sidra to south-east Italy and thence north-north-eastwards. At 1200 the wind at Malta decreased and the temperature fell 3°C whereas at Idris the wind increased and the temperature remained unchanged. The thickness field pattern (500–300 mb) showed somewhat irregular waves but thermal gradients were small. At 0001 2 June, the discontinuity had become associated with the main thermal trough extending from southern Italy to Cyrenaica.

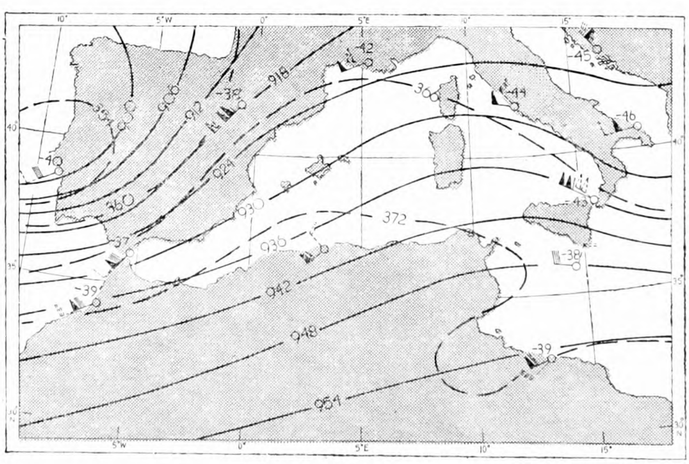

FIGURE 18—300 MB CHART FOR 0001 GMT, 31 MAY 1961
——— contours, —— —— 500–300 mb thickness, in geopotential decametres

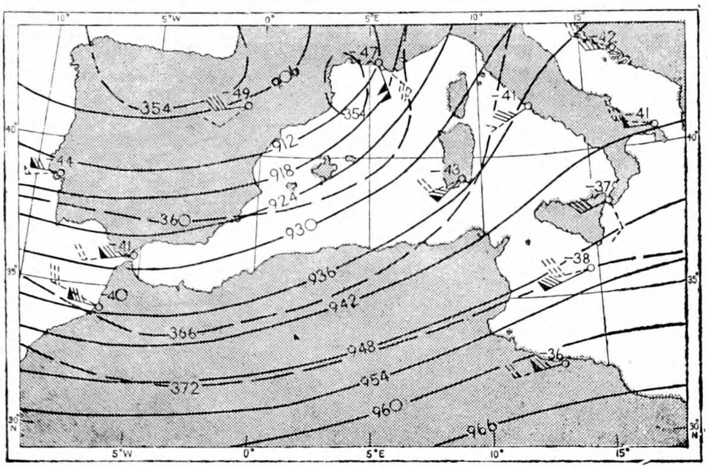

FIGURE 19—300 MB CHART FOR 0001 GMT, 1 JUNE 1961

——— contours, — — —— 500–300 mb thickness, in geopotential decametres

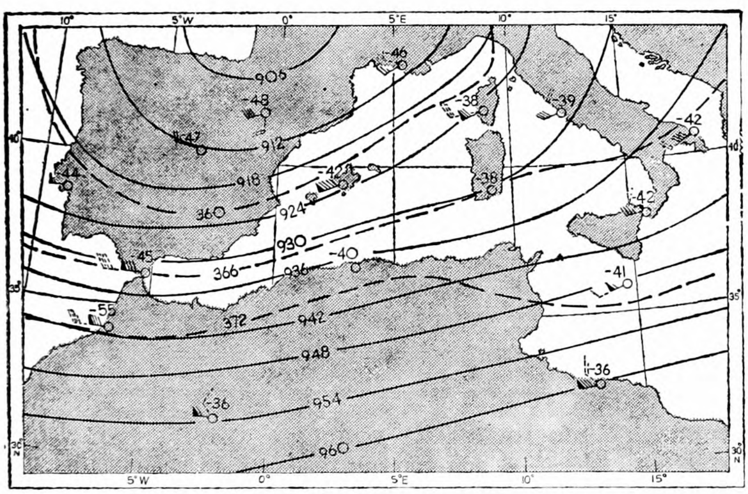

FIGURE 20—300 MB CHART FOR 1200 GMT, 1 JUNE 1961

——— contours, — — —— 500–300 mb thickness, in geopotential decametres

200 *mb*, *Figures* 21–23.—At 0001 31 May, the contour pattern was very similar to that at 300 mb but the thermal pattern over the central Mediterranean was most irregular and a sharp thermal trough was situated between Malta and Idris where a wind of 105 knots was observed, compared with 40 knots at Malta. At 0001 on the 1st, the main area of low thickness values (300–200 mb) extended from northern Italy through Yugoslavia to Cyrenaica, well ahead of the surface discontinuity as shown by the thermal wind at Malta. There was still evidence of a thermal trough between Malta and Idris although the light thermal wind at Idris suggests that it was much weaker. At 1200 the main thermal trough appeared to be associated with the surface discontinuity.

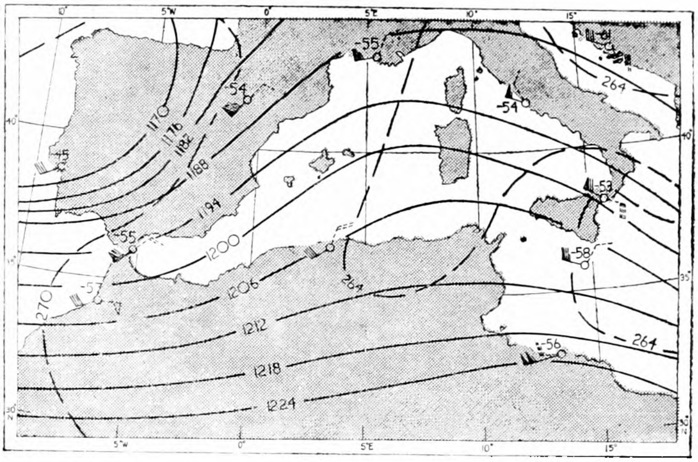

FIGURE 21—200 MB CHART FOR 0001 GMT, 31 MAY 1961
———— contours, —— —— 300–200 mb thickness, in geopotential decametres

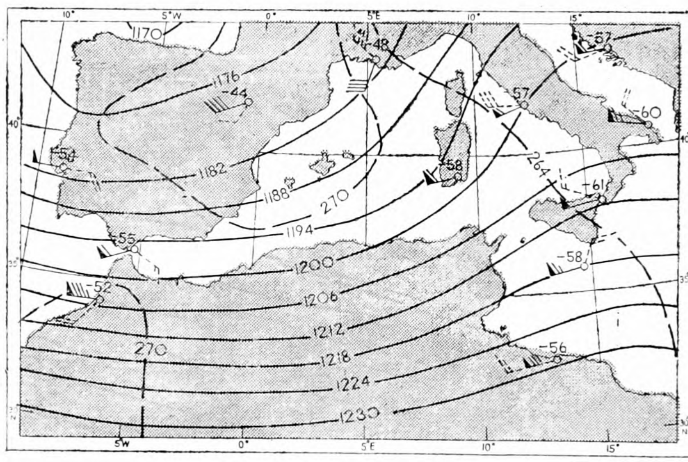

FIGURE 22—200 MB CHART FOR 0001 GMT, 1 JUNE 1961
———— contours, —— —— 300–200 mb thickness, in geopotential decametres

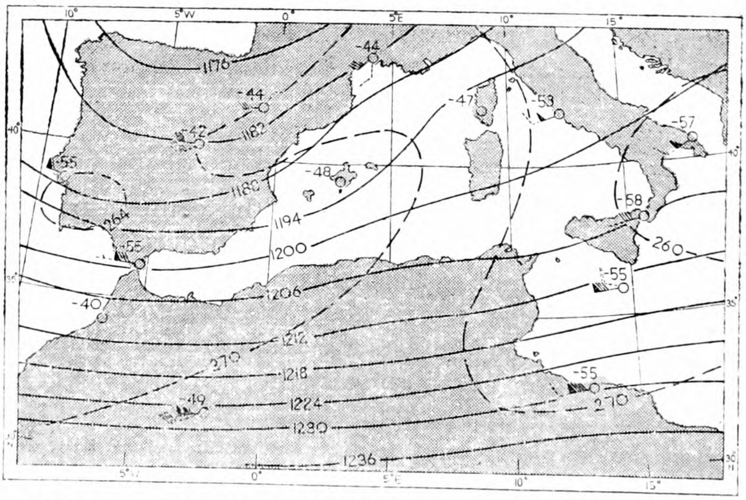

FIGURE 23—200 MB CHART FOR 1200 GMT, 1 JUNE 1961
———— contours, —— —— 300–200 mb thickness, in geopotential decametres

Conclusions.—Can any conclusions be drawn from this example? First of all, it would appear that the pressure jump has prognostic value for the subsequent passage of the surface cold discontinuity. The pressure jump occurred when a near-surface inversion was present and the height of the inversion was subsequently increased. The time of the upper air ascent at Qrendi (1130) does not permit an unambiguous distinction to be made between the changes accompanying the pressure jump and those due to the surface discontinuity, but it appears most probable that the sharp decrease in height of the tropopause occurred at the time of the pressure jump and that subsequent ascents (after 1200) showed the effect of the advection discontinuity by the continued decrease of temperature at most heights in the lower troposphere. This viewpoint is perhaps supported by the complete lack of evidence in the barogram for an advection discontinuity passing Malta although its presence at the surface was well attested by a sharp fall of temperature. These facts do not seem to lend much support to Tepper's[2] view of the surface front functioning mechanically as a piston to produce a shock wave on the inversion surface.

The evidence afforded by the charts shows that at 500 mb the thermal wave pattern was out of phase with that at 700 mb and at the time of passage of the surface discontinuity ('front') the 500 mb trough was certainly ahead of the latter. In seeking for explanations of the pressure jump we have two interesting possibilities, suggested by this example, in addition to the change in the low-level inversion of whose relevance we are already aware.[2] They are

(i) the sharp drop of tropopause height and

(ii) the occurrence of out-of-phase relationships at different levels.

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551.551.5:551.558.21:629.13

TURBULENCE NEAR DERNA ON 21 MARCH 1962

By M. GRIMMER

On 21 March 1962 a Shackleton aircraft was en route from Aden to Malta, having been diverted from El Adem because of strong cross winds on the runways.

At about 0600 GMT, 10 minutes after crossing the coast near Derna, the aircraft was in clear air at 4500 feet at position 33°05'N 22°15'E when, without any change in power setting, the airspeed increased from 140 to 200 knots and a slight climb was recorded. Almost immediately severe turbulence was suddenly encountered, culminating in three extemely severe bumps, in which 500 feet of altitude were lost, loose objects hit the roof, and radio contact with Malta was lost. The captain had no time to take any action before conditions became smooth again and the aircraft reached Malta without encountering any more than slight turbulence. On arrival the captain requested an airframe inspection, because he suspected damage to the main wing spars. He described the turbulence as far more severe than he had ever experienced, even in cumulonimbus.

For some time before crossing the coast, and up to the time of the incident, the navigator had found winds varying little from 220° 50 knots, measured by

Doppler radar. However, immediately afterwards he found a wind of 310° 15 knots, which quickly backed and strengthened to the previous value and little further change was found en route to Malta. The navigator was surprised at finding a north-west wind and rechecked it, so that it may be considered reliable.

At the time a surface depression of 994 mb was moving slowly in the Sicilian narrows and a strong southerly flow affected Cyrenaica ahead of an associated trough. At 0600 GMT a mean surface wind speed of 30 knots was reported from the south-south-east at El Adem with rising sand, while at Derna some 75 miles to the north-west, the wind was very light easterly, which clearly indicates the profound disturbance generated in a southerly flow by the high ground of Cyrenaica, which is generally above 1500 feet and reaches 2500 feet in places. (See Figure 7 on page 151.)

Aloft the winds over Cyrenaica were generally strong westerlies and above 10,000 feet the 0600 GMT winds at Tobruk showed a gradual veer and increased to 110 knots at 40,000 feet. However the lower winds revealed a more interesting structure with a subsidiary maximum of 190° 51 knots at 3000 feet decreasing and veering to 220° 26 knots at 10,000 feet. These winds agree well with those found by the navigator in the region of the coast.

A complex situation clearly existed at the time of the incident, and it is improbable that the turbulence is attributable to any single factor. However, certain effects may be mentioned as possible contributory factors:

1. Lee waves are suggested by the initially smooth build up of height and air speed of the Shackleton, but an examination of observations shows that conditions were far from ideal for their formation, because:
   (i) The winds, although increasing with height, were only perpendicular to the ridge below 10,000 feet.
   (ii) The Tobruk ascent for 0001 GMT on 21 March showed an inversion from the surface up to about 2000 feet (which is below ridge height) and conditional instability above that. Thus the l^2 parameter (Corby[1]) satisfies the lee-wave condition only because its values beneath the inversion were large, and not, as in the ideal case, because there is a deep stable layer whose top well exceeds the height of the ridge.
2. The facts that surface winds at Derna were light despite the strong southerly gradient, and that the aircraft experienced a north-west wind shortly after the incident indicate that a strong horizontal eddy was set up in the lee of the high ground.
3. Even if lee waves were not present, it is almost certain that a turbulent wake existed to the north of the high ground. Vertical turbulence would therefore be expected, but in the absence of some other mechanism it seems unlikely that turbulence of the type expected could be propagated as far upwind in the lee of the ridge, and to a height above ridge level.

It is not known whether an incident of this sort has been reported before, but it seems probable that it must occur to some degree in any strong southerly surface stream over Cyrenaica. It is the more hazardous to aircraft since dryness and therefore cloudlessness is a property of such airstreams and turbulence of any sort may be unexpected.

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551.543.5:551.551.5:551.558.21

SOME SYNOPTIC FEATURES OF AN OCCURRENCE OF LOW-LEVEL TURBULENCE

By T. H. KIRK

The incident, described by Grimmer,[1] in which an aircraft encountered severe low-level turbulence in clear air off the coast of Cyrenaica is particularly interesting because, in this instance, there is additional evidence which suggests that any explanation based solely on lee effects cannot be entirely adequate.

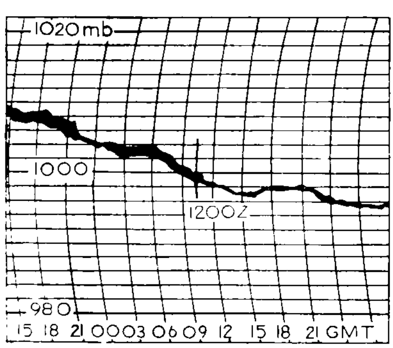
It is, of course, well known that severe turbulence does occur in waves to the lee of high ground. Quoting from a World Meteorological Organization Technical Note:[2] "Although flight through mountain waves may be deceptively smooth even when strong vertical currents are operating, it may also involve turbulence of an intensity as great as that generated in the worst thunderstorms."

Corby[3] also writes: "The rotor zone gives rise to the most severe turbulence to be found in the airflow over mountains and on occasions may be more violent than that occurring in the worst thunderstorms."

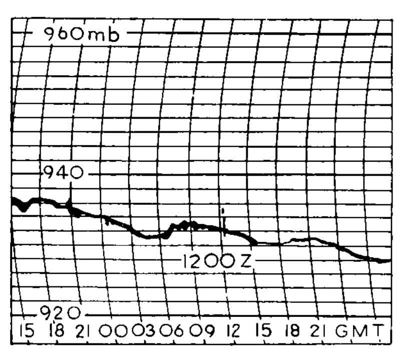
Sufficient evidence exists therefore for accepting the possibility of severe turbulence in mountain waves without seeking further causes. It is usual, however, to associate the worst turbulence with the first rotor zone, i.e. relatively close to the mountain. In this occurrence[1] the turbulence was encountered some 25 miles off the coast and this, in itself, is perhaps sufficient to suggest the possibility of other causative factors. That wave flow can break down suddenly giving rise to turbulence is well known:[3] "It appears that sometimes this breakdown operates simultaneously throughout the entire depth of the wave system and it may be associated with slight changes in the characteristics of the airstream when conditions are near the critical for waves to occur."

Synoptic evidence will be presented to show that a significant variation of the flow did in fact occur. One might accept the view that this variation could be responsible for the breakdown of the lee waves into turbulence as suggested above. On the other hand it may be that the variation is in itself a sufficient reason for severe turbulence and that the effect of the high ground is only of a contributory nature.

Figure 1 shows barograms for Derna — position 32°44'N, 22°38'E, height above M.S.L. 30 feet, and Shahat (Cyrene)—position 32°49' N, 21°51' E,



Derna



Shahat (height 2027 feet)

FIGURE 1—BAROGRAMS FOR DERNA AND SHAHAT, 21 MARCH 1962

height above M.S.L. 2027 feet. The Derna record, although a poor one, does show pronounced evidence of wave motion. It cannot, however, be assumed that the wave motion is due to lee waves of the normal type. The upper air ascent for Tobruk at 1200 GMT, 21 March 1962 (Figure 2) suggests the presence of a shallow inversion just below 900 mb (at about 3000 feet) and it is well established that wave motion can occur at inversions in the absence of the

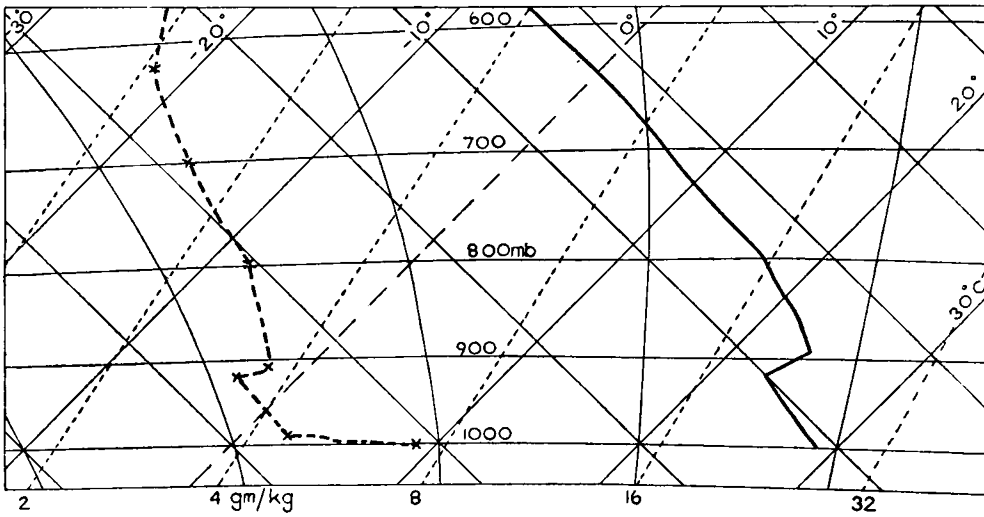
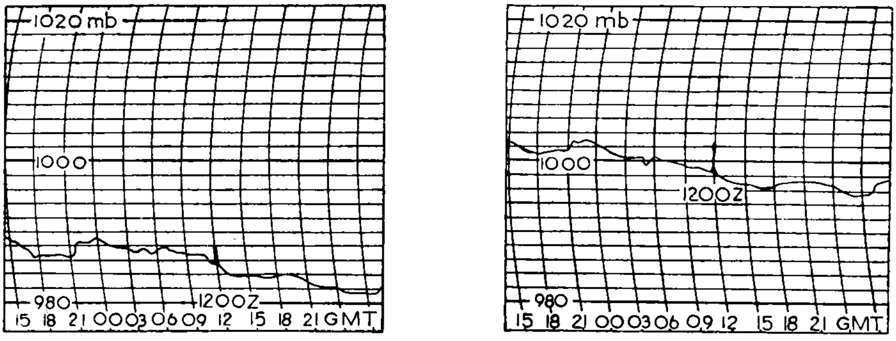


FIGURE 2—TEPHIGRAM FOR TOBRUK 1200 GMT, 21 MARCH 1962
——— dry-bulb temperature, – – – – dew-point temperature

disturbing influence of high ground. In fact, the presence of two quasi-autobarotropic layers separated by a shallow inversion provides the necessary conditions for the application of the hydraulic analogy.[4] The occurrence of gravity waves is therefore readily explicable and it is probable that the waves shown on the barometric record at Derna are of this origin.

Figure 3 shows the barograms for Benina—position 32° 44′N, 20°16′E, height above M.S.L. 425 feet, and Agedabia—position 30° 43′N, 20°10′E,



Benina Agedabia

FIGURE 3—BAROGRAMS FOR BENINA AND AGEDABIA, 21 MARCH 1962, SHOWING PRESSURE JUMPS

To face p. 148

BIRMINGHAM (EDGBASTON) AUXILIARY REPORTING STATION

Mr. A. L. Kelley, Director of the Edgbaston Observatory is standing beside the screens. The anemometer can be seen on the distant tower just to the right of the screens. Continuous records have been maintained here since 1887.

Photograph by P. T. Hutton

EXAMPLES OF LIGHTNING AT CHANGI, APRIL 1956

The lightning flashes shown in these photographs are not uncommon during the thunderstorm season at Changi. Time exposure 30 seconds.

Photograph by P. T. Hutton

EXAMPLES OF LIGHTNING AT CHANGI, APRIL 1956

The lightning flashes shown in these photographs are not uncommon during the thunderstorm season at Changi. Time exposure 30 seconds.

To face p. 149

FLEETWOOD (LANCASHIRE) COASTGUARD LOOKOUT

Situated on the sand dunes alongside the beach, on the west side of the town. Meteorological observations began on 1 January 1961.

height above M.S.L. 15 feet. Of immediate interest are the pressure jumps at or near 2100 GMT on 20 March. These afford confirmation of the occurrence of gravity waves at an interface and are direct evidence of a disturbance in the airflow independent of the topography. Before commenting on the origin of these pressure jumps it may be useful to examine the synoptic situation.

Figure 4 shows the surface chart for 2100 GMT on the 20th. The line marked *A* – – – *A* – – – *A* is not a front according to temperate–latitude usage but an advection discontinuity. It has been drawn to be consistent with the passage of the pressure jumps at Benina and Agedabia. It may be regarded as a 'pressure jump' line[4] and, across it, the isobars have been drawn 'discontinuous' in the manner already used by Freeman.[5] The subsequent situations at 0001, 0300, 0600 and 0900 GMT are shown in Figures 5, 6, 7 and 8 respectively.

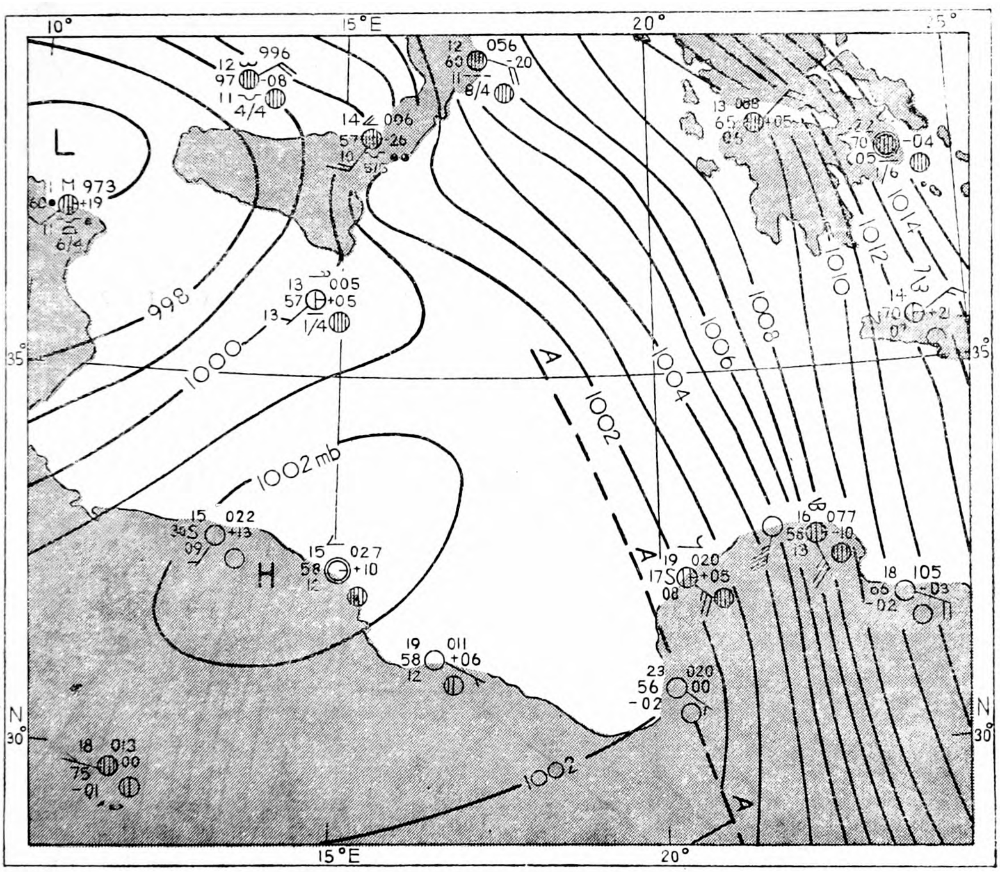


FIGURE 4—SURFACE CHART FOR 2100 GMT, 20 MARCH 1962
A – – – – *A* advection discontinuity

The sparsity of the evidence for adopting this procedure is appreciated and for this reason it is necessary to consider the 850 mb charts for 1200 GMT on the

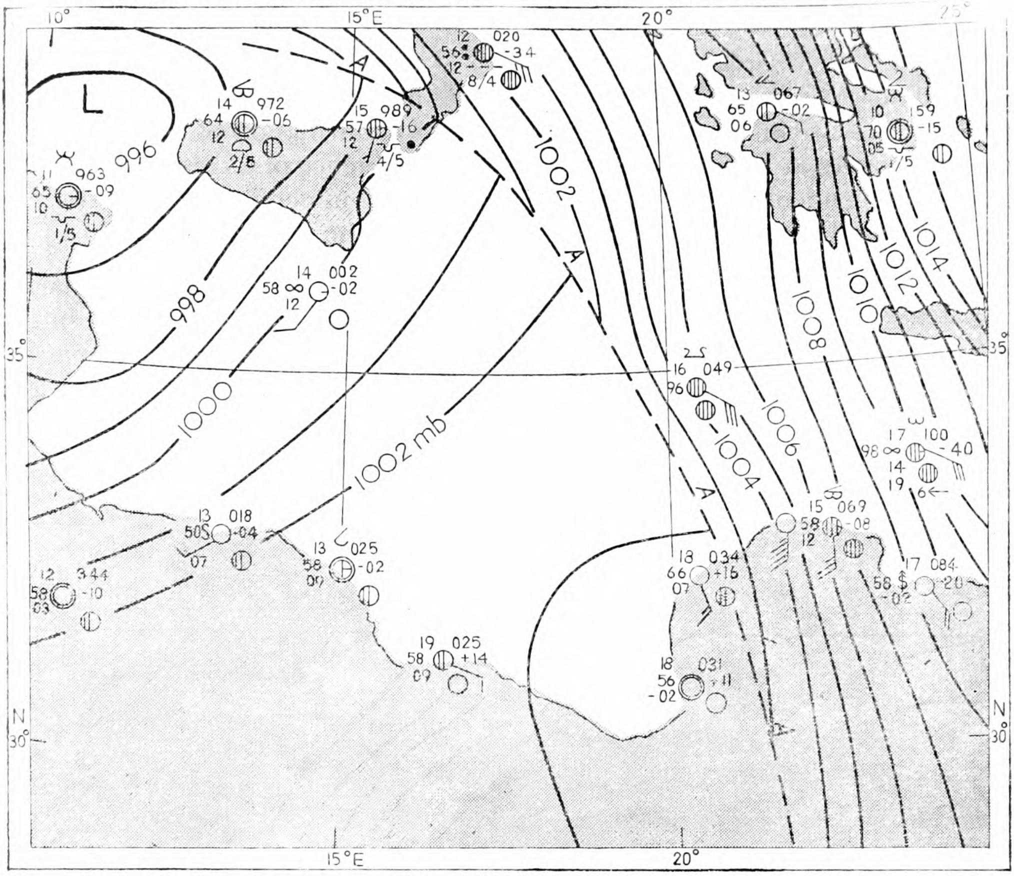


FIGURE 5—SURFACE CHART FOR 0001 GMT, 21 MARCH 1962

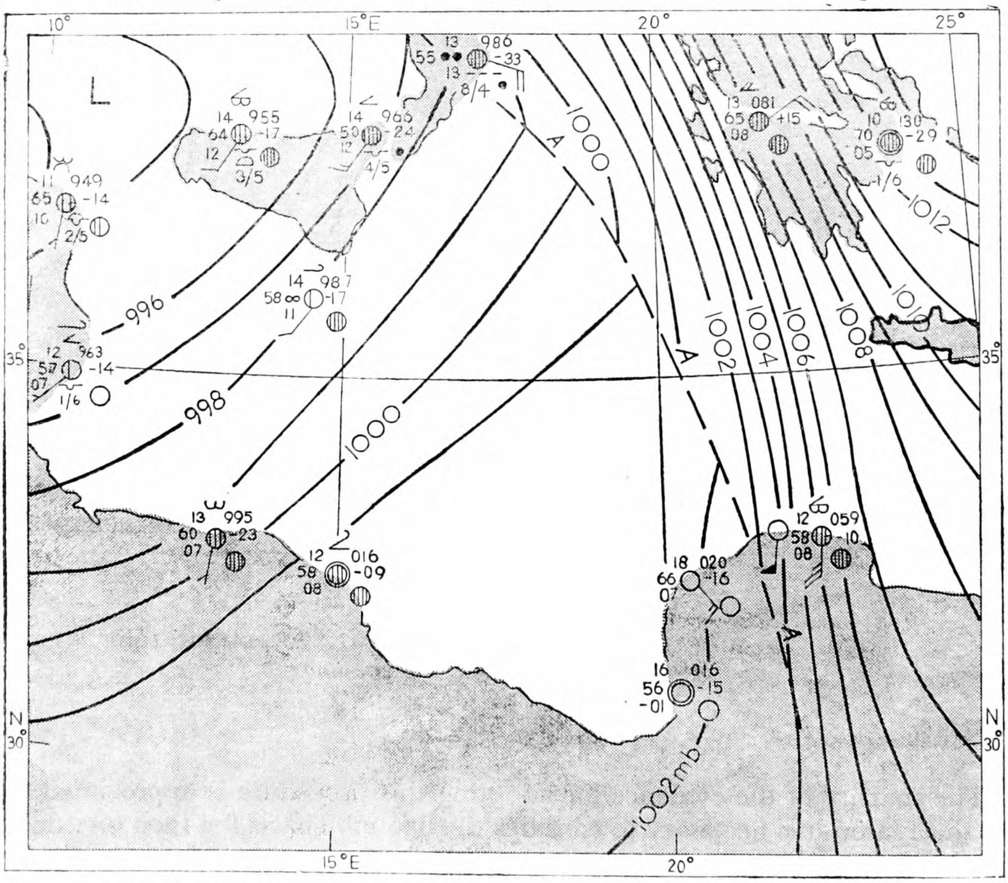


FIGURE 6—SURFACE CHART FOR 0300 GMT, 21 MARCH 1962

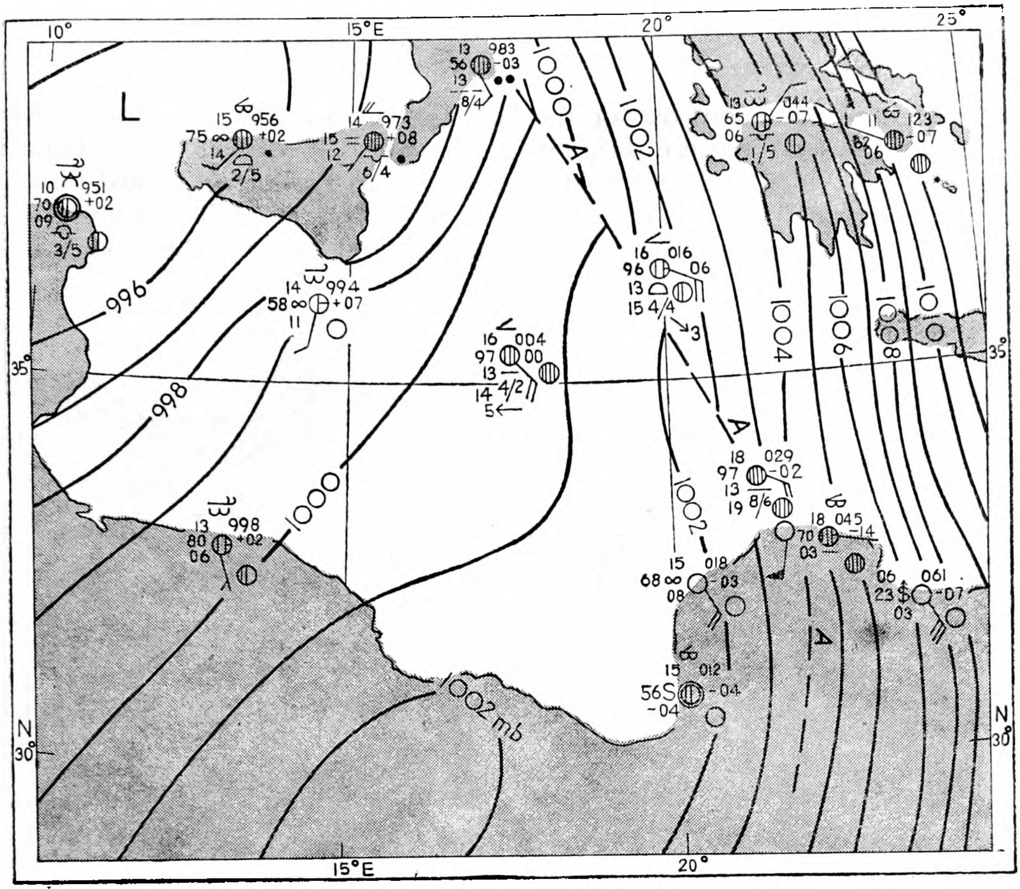


FIGURE 7—SURFACE CHART FOR 0600 GMT, 21 MARCH 1962

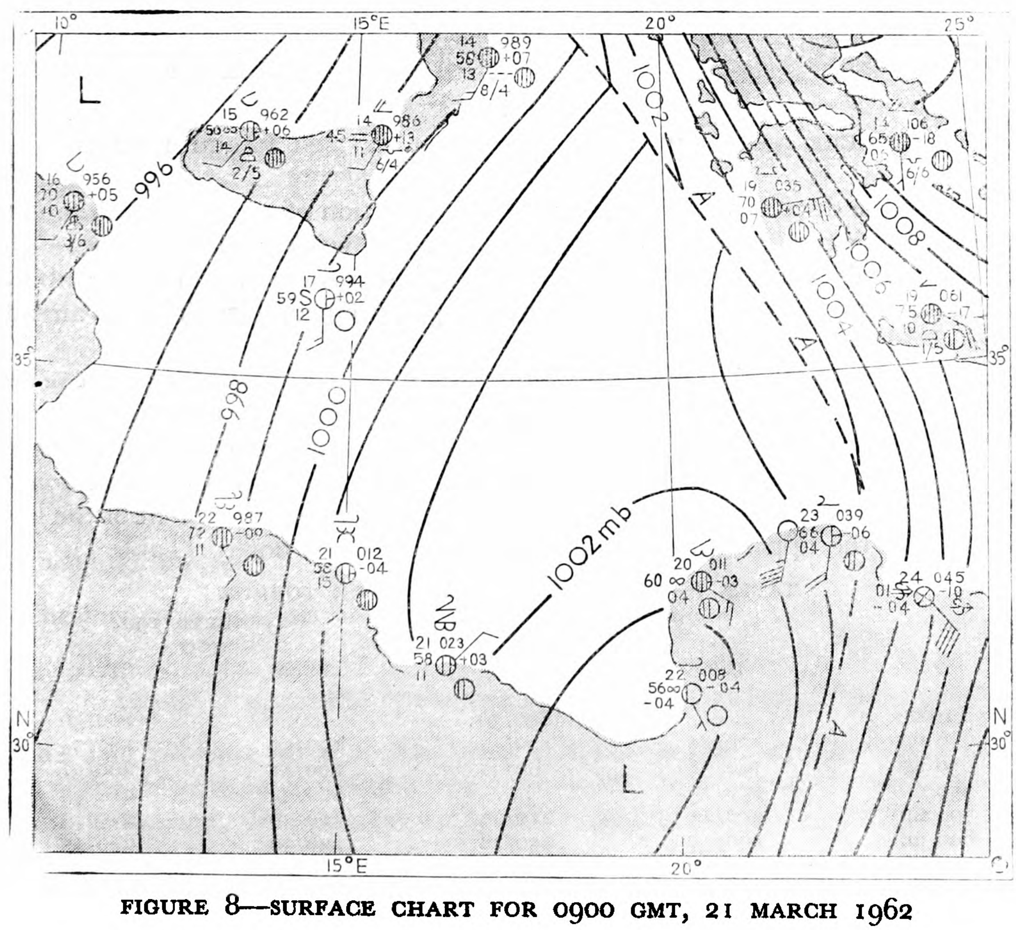


FIGURE 8—SURFACE CHART FOR 0900 GMT, 21 MARCH 1962

20th (Figure 9) and 0001 GMT on the 21st (Figure 10). The rapid transference of the trough over western Tripolitania eastwards to eastern Tripolitania is immediately evident. The isotherms as drawn in Figure 10, copied directly from the working chart, show the existence of an 'advection discontinuity' (i.e. a discontinuity in the thermal advection field) at or near the trough line.

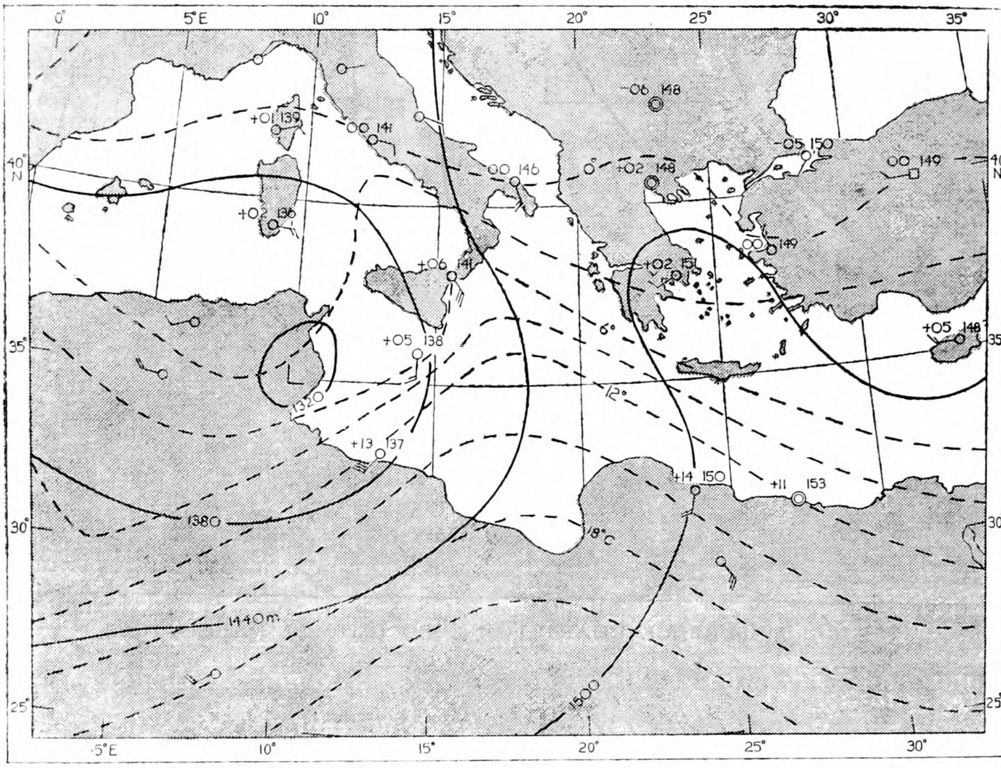


FIGURE 9—850 MB CHART FOR 1200 GMT, 20 MARCH 1962
——— contours, – – – – isotherms

Ahead of the discontinuity there is a strong advection of warm air maintaining a thermal ridge; behind it the pattern is one of weak cold advection. The occurrence of a warm ridge ahead of a trough line is suggestive of the instability line[6] and the association of the 'pressure jump' with instability lines has already been demonstrated by Tepper.[4]

As for the origin of the pressure jumps there are two possibilities not necessarily independent. They may be due to the acceleration and sharpening of the trough at the 850 mb. level. On the other hand Tepper[7] has also shown the possibility of pressure jumps resulting from the impulsive addition of momentum to a southerly flow. In this connexion the development of the low-level jet in the upper wind values for Tobruk may be noted, (Table I).

TABLE I—UPPER WIND VALUES FOR TOBRUK

	20 March 1962 GMT		21 March 1962 GMT	
	1800	0001	0600	1200
		degrees/knots		
Surface	...	150/30	...	180/30
900 mb	160/34	170/42	190/51	180/54
850 mb	190/31	180/37	200/41	200/51
750 mb	190/25	...	220/34	210/45
700 mb	200/23	210/29	220/26	210/43
600 mb	200/23	250/28	230/30	220/45

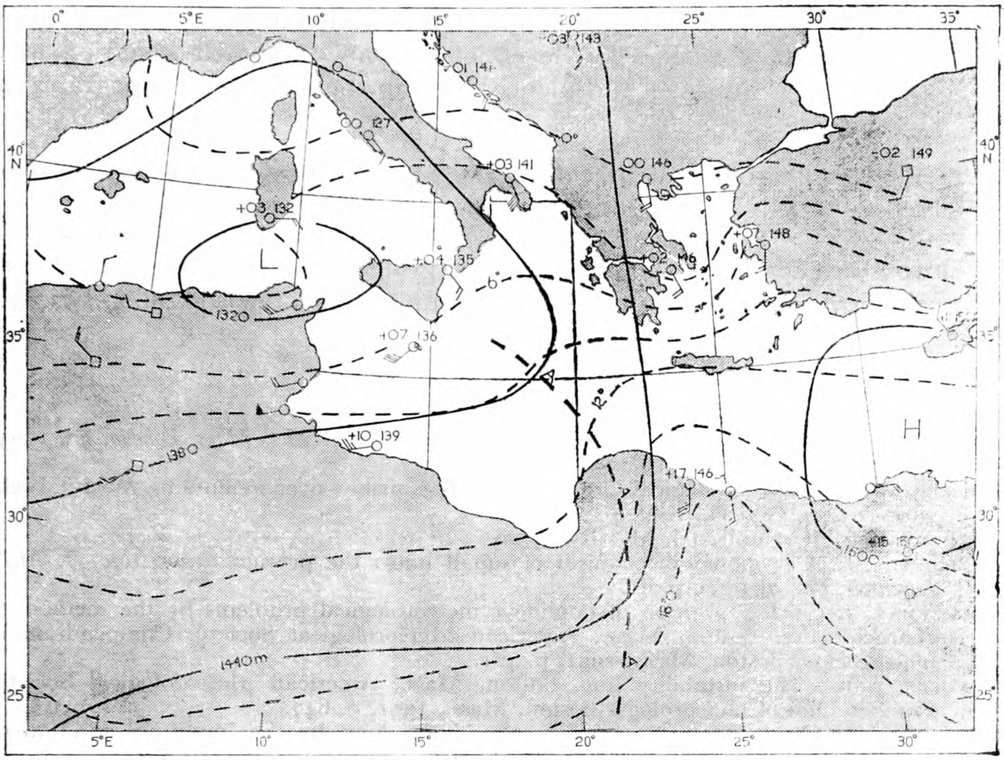


FIGURE 10—850 MB CHART FOR 0001 GMT, 21 MARCH 1962
——— contours, – – – – isotherms
A – – – – *A* advection discontinuity

At Shahat, a high-level station west of Derna, surface winds of over 40 knots from 180° were reported at all synoptic hours between 1500 GMT on the 20th and 0900 GMT on the 21st.

The assertion can now be made that the evidence suggests the association of the turbulence with a line disturbance of the flow. It is known that instability lines are significant for turbulence. Although the associated terms 'instability line' and 'squall line' are almost always used when thunderstorm activity is in evidence, the pressure-jump mechanism is itself independent of precipitation and there appears to be no reason to doubt the relevance of the pressure jump for low-level turbulence even in clear air.

The extent to which the topography in this instance was a contributory factor is unknown and discussion on this point would be unprofitable without further information.

The foregoing analysis illustrates the following points:

(i) The synoptic method of analysis sometimes can be usefully employed in the investigation of phenomena normally regarded as 'meso-scale'.

(ii) The 'pressure jump' line or instability line (a not uncommon feature in the Mediterranean but often unnoticed[8]) has relevance for low-level turbulence, even in clear air.

(iii) The Mediterranean forecaster would be justified in recognizing a strong southerly flow with a low-level jet and an associated inversion as a situation for low-level turbulence, even in the absence of topographical influences.

(iv) Where topographical effects can be expected the situation (iii) must be regarded as highly significant for severe turbulence.

Acknowledgement.— The author is grateful to the Director, Libya Meteorological Service, for providing autographic records and synoptic reports.

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551.501.45:551.573

ESTIMATES OF THE POTENTIAL TRANSPIRATION IN THE MONTH OF MARCH FOR TWO PLACES IN SCOTLAND

By R. W. GLOYNE and N. M. McSWEEN

Introduction.—There is considerable interest, especially in the drier parts of Scotland, in the likelihood of soil moisture deficits in the month of March. However, the simple method of estimating potential transpiration (by a linear regression on sunshine) is not valid in the 'winter' half year (October–March), whilst the data necessary for a full computation by Penman's method require more extensive instrumentation than is available at most climatological stations. Accordingly, an alternative approach is needed, and in this note the relationships between estimated potential transpiration given by the complete calculation and that given by the 'aerodynamic' term, are presented for two places in Scotland.

The argument adopted in an earlier paper by Penman[1] has recently been substantially modified.[2] The earlier paper forms the basis of estimates given in two publications of the Ministry of Agriculture, Fisheries and Food.[3,4] Briefly he allows for the 25 per cent reflection of short-wave solar and sky radiation from a green crop surface by applying a factor of 0.75 to that incident upon such a surface, but omits all reference to the seasonal constant f (< 1.0), previously used to convert evaporation from an open water surface to potential transpiration losses from the crop. The opportunity has been taken to examine the effects of these changes in specific cases.

The several expressions for two stations in Scotland, namely Tiree and Leuchars (Fife), for the month of March were computed thus:

E_{T1} = potential transpiration according to the earlier (1948) formulation (Penman[1]),
E_{T2} = potential transpiration according to the recent (1962) formulation (Penman[2]),
E_a = the 'aerodynamic' term (common to both formulations) where
$E_a = 0.35\ (1 + \bar{u} \times 10^{-2})\ [e_a - e_d]$ mm of water/day,
and $\bar{u}$ = mean run of wind in miles per day at six feet over a grass surface,
e_a = saturation vapour pressure (in mm of mercury) corresponding to the mean air temperature, and
e_d = vapour pressure corresponding to the mean dew-point.

Results.—As is customary, all quantities were converted into inches of water per month. The results are for the month of March and based upon values for the period 1930–62 inclusive.

Leuchars

$E_{T2} = 1.24\ E_{T1} - 0.13$ $\quad \overline{E}_{T2} = 1.06$ $\quad \overline{E}_{T1} = 0.96$
$E_{T2} = 0.43\ E_a + 0.38$ $\quad \overline{E}_a = 1.58$

Tiree

$E_{T2} = 1.40\ E_{T1} - 0.30$ $\quad \overline{E}_{T2} = 1.28$ $\quad \overline{E}_{T1} = 1.12$
$E_{T2} = 0.48\ E_a + 0.33$ $\quad \overline{E}_a = 1.98$

(bars over the symbols indicate mean values).

In each case, the regressions account for over 95 per cent of the total variance.

Discussion.—Although the regression coefficients in the E_{T2} and E_{T1} equations are relatively large, in absolute terms the resulting differences rarely exceed 0.2 inches per month and may be considered insignificant. The exceptional cases, which relate to Tiree, are:

March 1938	$E_{T1} = 1.62$ in.	$E_{T2} = 2.04$ in.
March 1958	$E_{T1} = 1.70$ in.	$E_{T2} = 2.11$ in.

On these occasions, both the wind speed and the vapour pressure deficit (and hence E_a) were amongst the highest values for the whole series.

A comparison for a shorter (1930–47) series for the month of May at Leuchars gave:

$E_{T2} = 1.10\ E_{T1} - 0.30$ $\quad \overline{E}_{T2} = 2.71$ in. $\quad \overline{E}_{T1} = 2.73$ in.

and again, in absolute terms, the estimates agree closely. However, the scatter is rather greater than for March results.

With respect to estimates for the month of March in southern Scotland, the analysis indicates that:

(*a*) The alterations in the basis of Penman's formulation lead to only small *absolute* differences.

(*b*) The 'aerodynamic' formula allows a good approximation to estimates of potential transpiration arrived at using more complicated procedures.

In connexion with statement (*a*), Grindley[5] notes that some provisional results for southern England also show small absolute differences. However, there are indications that the pattern of seasonal differences over Great Britain as a whole may not be uniform.

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GLIDER OBSERVATIONS OF LEE WAVES IN AND ABOVE A FIELD OF CUMULUS CLOUD

By T. A. M. BRADBURY

The existence of lee waves and active convective currents at the same level, and close together, is probably uncommon over the British Isles. It is usually considered that morning heating inhibits the development of lee waves. An essential requirement for strong lee waves is that there should be marked stability at the levels where the air is disturbed by the mountains.[1] The following observations may be of interest because the lower level of lee-wave flow occurred in the middle of a summer afternoon in a layer where active convective clouds existed.

At 1200 GMT on 22 August 1962 the British Isles were under the influence of an eastward moving ridge which lay between an occluded front over the North Sea, and an advancing warm front west of ocean weather station Juliett (Figure 1). The upper air soundings made at this time at Aughton, Camborne

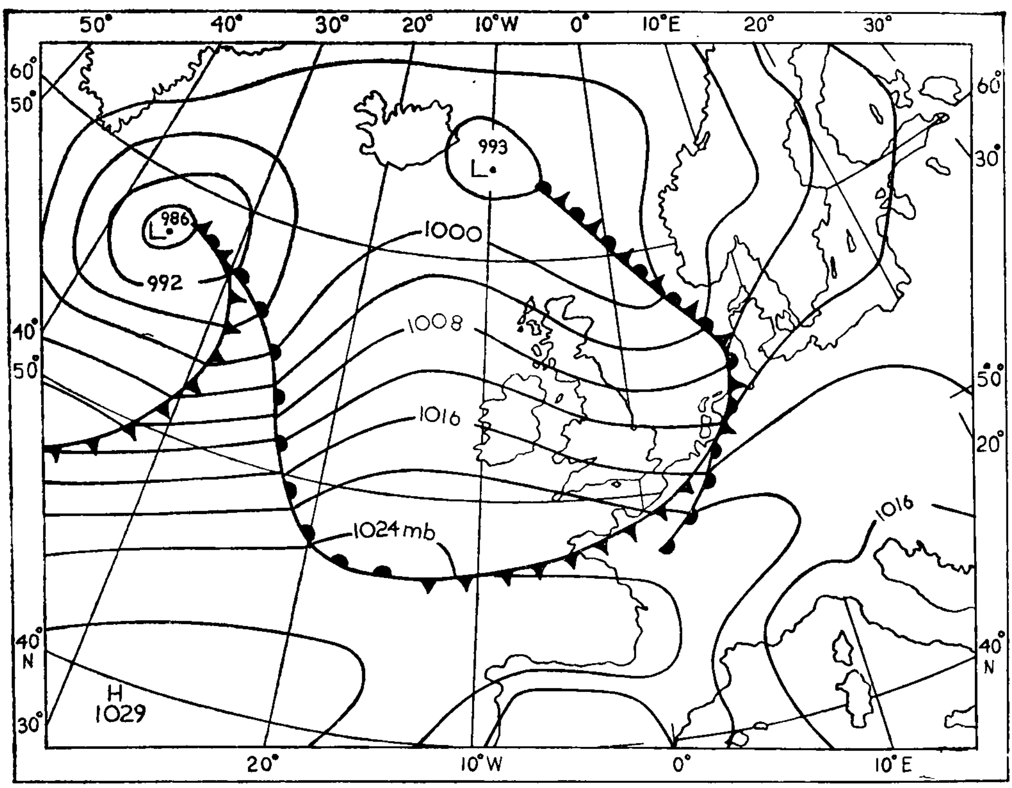

FIGURE 1—SURFACE CHART FOR 1200 GMT, 22 AUGUST 1962

and Valentia all showed an unstable layer at low levels, capped by a stable layer, with reduced stability aloft. In general the level of the stable zone sloped upwards from south to north across England, and lowered to the west over Valentia. The winds aloft were almost constant in direction, increasing with height. The tephigrams for Aughton and Camborne are shown in Figure 2.

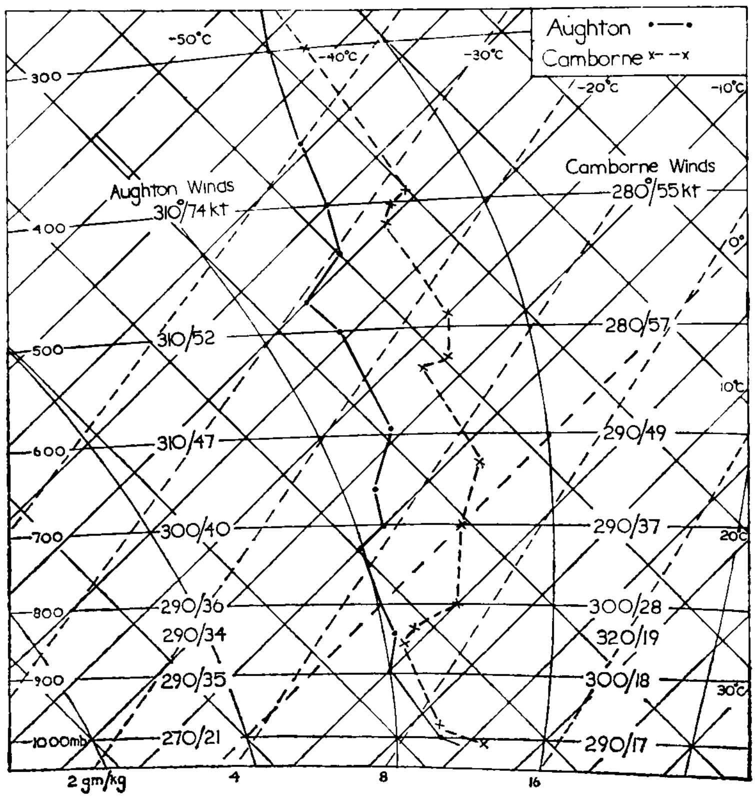

FIGURE 2—TEPHIGRAM FOR AUGHTON AND CAMBORNE, 1200 GMT 22 AUGUST 1962

The glider flight covered the area from Nympsfield (near Stroud), to Ross-on-Wye, Hereford, Bromyard, Tewkesbury and back to Nympsfield, during the period 1250 to 1725 GMT. The machine was a standard class (15 metre span) glider of the type Slingsby Skylark II, fitted with a sensitive electric variometer and carrying a recording barograph. The heights recorded were taken from the barograph trace.

Visual observations between 1300 and 1400 GMT showed active cumulus clouds extending up to 7500 feet above mean sea level over the Cotswolds and to 7000 feet west of the River Severn, with some cumulus streets of a few miles in length lying along the wind direction. The first wave was encountered at 1410 GMT near Cinderford over the position 51°50′N, 02°30′W at 5800 feet above mean sea level. The smooth up-current occurred in a region of clear air less than half a mile upwind of an active cumulus street extending up to about 7000 feet. The lower part of the wave flow was therefore some 1200 feet below the cloud top, and presumably the wave trough dipped even further down. Airflow in, and adjacent to, the cumulus street was found to have an upward component of at least eight knots in the active part of the cloud, with a small downward flow just outside and in the extreme edge of the cloud.

The vertical velocity of the air is based on the assumption that the sinking speed of the glider was 1.7 knots when flying level at about 40 knots. This assumption is not likely to introduce great errors when flight is in smooth air, but in cumulus cloud, when turning at 30 to 40 degrees of bank the rate of sink is probably nearer 2.5 knots.

Flying into wind at about 40 knots indicated air speed the glider climbed to 9100 feet above mean sea level remaining in clear air throughout. The average rate of ascent of the air was just under 3 knots, less at first, but increasing to a maximum of 4.2 knots between the levels 7200 and 7700 feet. Seen from above, the cloud structure showed no indication of the existence of the wave flow. There was no definite pattern in the distribution of cumulus cells, and individual clouds appeared to be travelling with the wind, so far as could be judged from the movement of cloud shadows on the ground.

The glider passed over at least one moderate sized cumulus cloud when moving upwind to the next wave. This wave was reached at 1441 GMT near Ross-on-Wye, over the position 51°53'N, 02°36'W at a height of 6500 feet, about 500 feet below the tops of surrounding cumulus cloud. It is surprising to note that one cumulus appeared to be under the downflowing part of the wave. The upward velocity of the air in the second wave near Ross was initially about 5 knots, with a mean velocity of 3.9 knots up to 7600 feet; above this level it decreased to less than 2 knots.

A more active region of the wave was presently found along a line running approximately NNE–SSW through the position 51°58'N, 02°37'W. Here the mean upward velocity averaged 3 knots through a band from 8000 to 9900 feet. The maximum altitude was reached near Hereford at 1544 GMT when the barograph recorded 11,700 feet above mean sea level, over the position 52°02'N, 02°38'W. Figure 3 shows a cross-section through Ross-on-Wye. From Hereford decreasing wave lift was followed to a position about 52°10'N, 02°31'W, near Bromyard, where the up-current was lost and not again located.

At this time a thickening sheet of cirrus cloud caused a marked reduction of insolation and the cumulus began to decay. As this process continued some clouds began to be modified by the wave flow aloft. No lenticular shapes were seen to the west, but the axis of the wave crest near Ross-on-Wye became evident along a line (approximately) 51°56'N, 02°33'W to 52°00'N, 02°31'W. Above the lenticular top of this cloud the mean upward velocity found was just under 3 knots between the levels 8300 to 9700 feet, with a maximum of 4.2 knots. At 1610 GMT the up-currents near Ross died away, and there was a corresponding disintegration of the wave-form cloud below.

No wave effects were observed in the original area near Cinderford, but a new system developed downwind. This was marked by a very small wisp of lenticular cloud, which formed at 1630 GMT and developed rapidly into a bar of classical shape. In about ten minutes this cloud extended along the line 51°53'N, 02°18'W to 52°02'N, 02°12'W, lying over the Vale of the Severn, mainly west of the river. The glider penetrated the lower part of this cloud as it was forming and experienced some turbulence inside, but the airflow

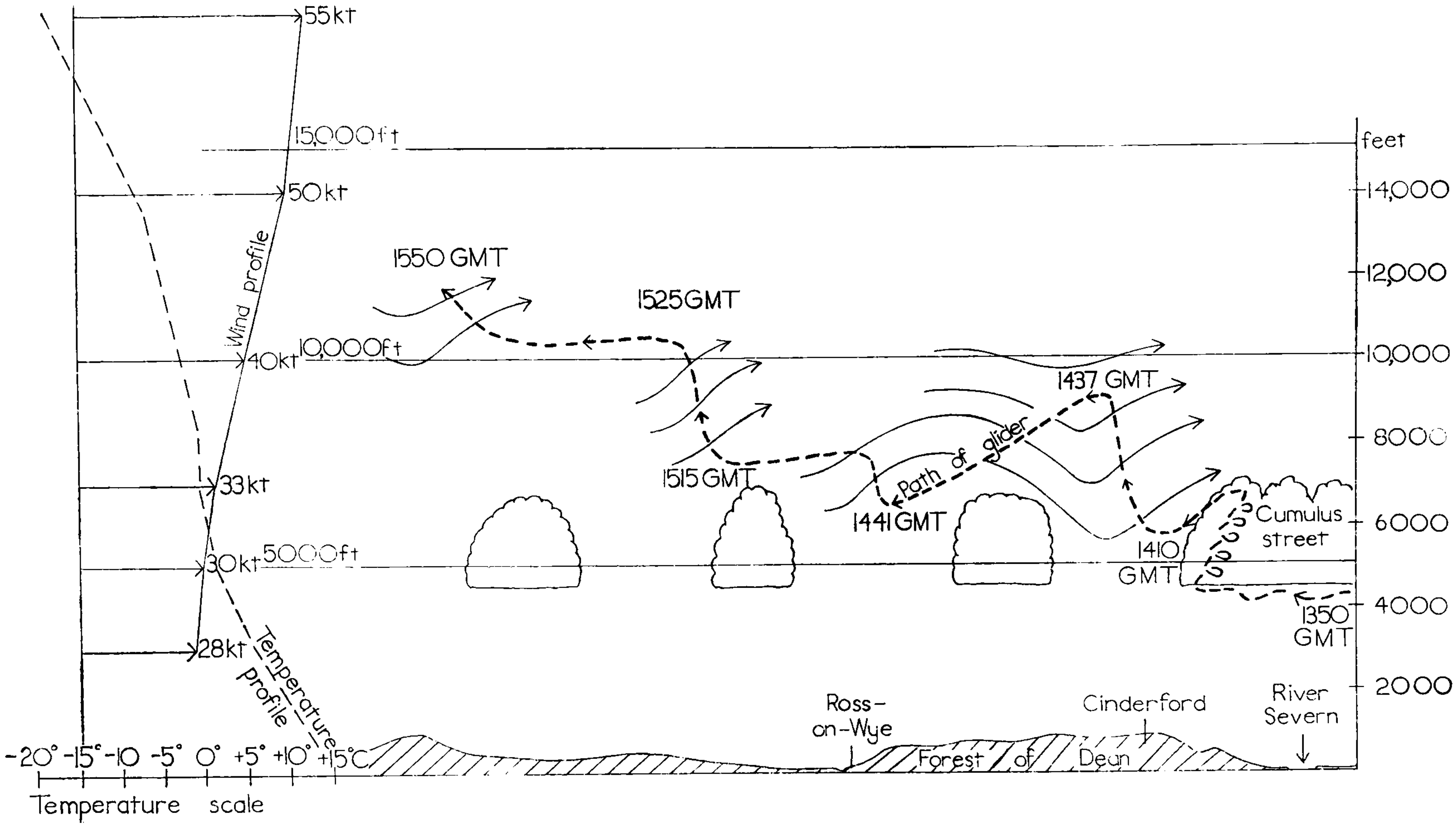

FIGURE 3—NORTH-WEST TO SOUTH-EAST CROSS-SECTION
Showing clouds and suggested airflow 1350–1550 GMT, 22 August 1962 with profiles of wind and temperature.

resumed its characteristic smooth nature at the upwind edge of the cloud, and over the top of it. The maximum observed up-current was just over 5 knots, with an average of 3.4 knots from 6500 to 7700 feet. The fully developed wave flow lasted only about 15 minutes after which the up-current died away and the cloud degenerated into ragged stratocumulus with some turbulence in the lower layers. A final wave cloud was later observed to have formed along the line of the Cotswold edge near Cheltenham, but this wave was not explored. The glider returned to Nympsfield and landed at 1725 GMT. Between 1710 and 1725 the clouds dispersed almost completely, leaving a single bar of lenticular cloud in the direction of Ross-on-Wye, and some smaller clouds near the Malvern hills.

Figure 4 shows the positions of wave lift encountered. An estimate of the conditions over Herefordshire was obtained by interpolating between the values reported from the soundings at Aughton and Camborne. From this interpolation values of Scorer's[2] parameter l^2 were obtained using the lee-wave

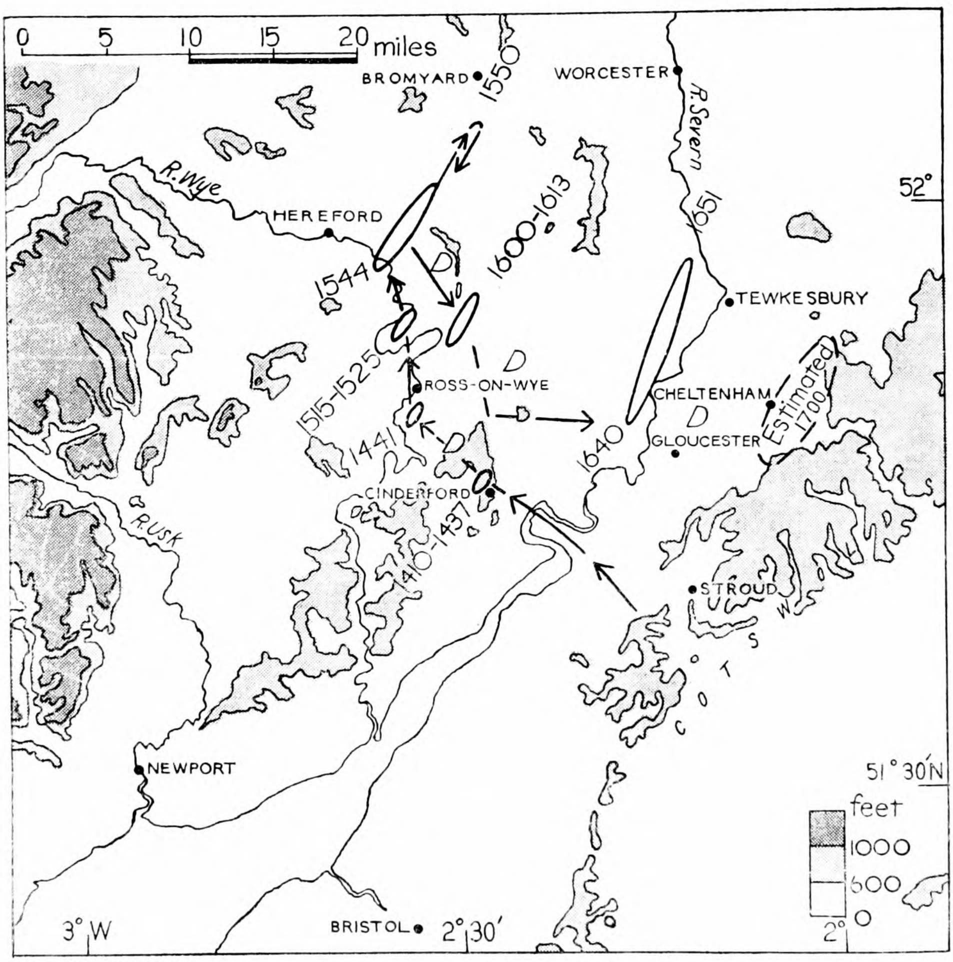

FIGURE 4—LEE-WAVE OBSERVATIONS ON 22 AUGUST 1962

Positions of ascending air outlined and annotated with the duration of the ascent in the up-current. Areas of descending air are marked with a *D*.

scale devised by Wallington.[3] It was found that l^2 increased to a maximum in the layer 790–740 millibars, and then decreased to about one-eighth of this between 610 and 490 millibars. One would expect to find the greatest amplitude of lee waves in the layer 790–740 millibars, and this is borne out by the barograph trace which showed the best rate of climb in the first wave between 7200 and 7700 feet.

It is difficult to suggest any particular mountain slope as the origin of the waves. The Welsh mountains extend some fifty miles upwind of Herefordshire, with peaks of 2000 to 2500 feet. The natural wavelength of the air was probably changing with the approach of the Atlantic warm front (Wallington[4]), and if so it is likely that the wavelength was periodically in phase with the topography. This would account for the apparently irregular wavelength. The most interesting feature however was the existence of lee-wave flow at a level well below the top of the cumulus cloud, and the fact that the waves occurred at a time of maximum convection, when the cumulus tops extended at least 4000 feet above the upwind mountains.

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WORKING GROUP ON COLLECTION AND PROCESSING OF MARINE CLIMATOLOGICAL DATA

A session of the World Meteorological Organization (WMO) Working Group on the collection and processing of marine climatological data was held at the WMO Secretariat from 14–18 January 1963, under the chairmanship of the President of the Commission for Marine Meteorology (CMM), Mr. J. A. van Duijnen Montijn of the Netherlands. Members attended from the U.S.A., Netherlands, Norway, United Kingdom, India, Federal Republic of Germany, South Africa and Japan. Mr. F. E. Lumb of the Meteorological Office represented the United Kingdom.

The task of the Working Group was to study the technical and financial aspects of a plan to divide the oceans into areas of responsibility for the collection and processing of marine climatological data. This plan arose from a recommendation of CMM which proposed that the oceans and seas be divided into areas of responsibility, and the main maritime countries (known as Responsible Members) be invited to assume responsibility for one of these areas. For example, the United Kingdom could be responsible for the North Atlantic east of 50°W, and the Mediterranean. Each Responsible Member would collect punched cards (using the International Maritime Meteorological Punch Card which was brought into use as from 1 January 1962), for all ships' observations, of whatever nationality, made in that area. The Responsible Members would also prepare monthly climatological summaries each year for a number of ocean sub-areas, chosen so as to ensure as far as possible a sufficient number of observations to enable useful summaries to be given.

Agreement was reached on a number of items discussed and a draft Resolution embodying the decisions of the Working Group was drawn up for consideration by WMO Fourth Congress.

METEOROLOGICAL OFFICE DISCUSSION

The search for practical solutions in agricultural meteorology

The second Monday Discussion of the winter took place at the Royal Society of Arts on 17 December 1962. Mr. W. H. Hogg opened the discussion with brief descriptions of three widely different types of work with which he had been associated at Bristol, in collaboration with various members of the Ministry of Agriculture, Fisheries and Food. The first dealt with the meteorological aspects of the epidemiology of Black Stem Rust of Wheat. This investigation was based on the use of geostrophic trajectories from surface, 700 mb and 500 mb charts over the period 1947-59 and in general terms it was possible to relate the frequency of trajectories from Spain and Portugal to the severity of the disease in south-west England; the date of observation of the disease was some few weeks after the occurrence of trajectories from these sources. For the period 1955–59 a comparison of trajectories with spore catches showed a close connexion between the catches and trajectories from a southerly or south-easterly direction. In years such as 1955 with an early epidemic, the origin of the spores was probably in Spain or Portugal; in years of later appearance, the inoculum may have originated in France. It was stated that there were difficulties in interpreting results for 1956, when light catches of spores were apparently associated with Atlantic trajectories. A surprisingly close relationship between short-period variations in spore catch in London and trajectory direction over the period 4–10 July 1959 was demonstrated.

The second topic discussed by the opener was based on observations from Rosewarne Experimental Horticulture Station at Camborne and concerned the effects of shelter on the climate. An attempt was made to estimate the geomorphic shelter provided by valleys in a plateau with a general level of about 250 feet. Two years' observations suggested that when all wind directions are considered, the sheltered sites have a run of wind 13–15 per cent below that at the open site; individual directions show greater variability according to position of the sites. A further investigation is now being carried out within an area sheltered by hedges and one of the most interesting points so far noticed is increase of soil temperature during the summer. This may be as much as 2–4°F at 2 inches depth and is still perceptible at 8 inches. In view of these differences it was suggested that a shelter index should take account of factors other than the reduction of wind speed.

The Meteorological Office at Bristol is co-operating in a survey of potential horticultural areas in England and Wales and the methods used in this type of work were outlined. The study is confined to the physical factors of climate, site, soil and water supply, and demands both a general survey of existing information and a field survey. In the meteorological context, the former provides a macroclimatic background which is then confirmed or modified by field assessments of mesoclimate. The general survey is based on standard meteorological data but these are generally of far more value when adapted; for example, the use of degree-days below 60°F can provide a measure of coal needed to produce glasshouse crops, and rainfall and sunshine data are best combined in order to compute water-balance sheets. With regard to frost, the best generalized assessment appears to be one based upon a division of the country into donor and reception areas of cold air, and this is being attempted on 1:25,000 maps.

Field work has involved some reassessment of water needs when soil types are brought under consideration, and frost risk may need to be modified if air movement is impeded by factors not obvious from maps. Some detailed knowledge of the frequency of inversions and their depths during spring would be a great help here. In making field assessments of exposure, some visual aid is provided by wind-pruning of trees and it has sometimes been possible to define areas which are too exposed for horticulture. One of the final aims of the survey is to produce a series of maps showing the areas suitable for horticultural development and a few specimen maps for Devon and Cornwall were shown.

The discussion ranged over a wide field and there were many contributions from visitors interested in agriculture. Dr. Hirst elaborated on some of the aerobiological aspects of spore travel and distribution, and other work being carried out in agrometeorology was referred to, particularly in relation to plant disease and animal comfort. An important practical point which emerged from the discussion concerned the accuracy of meteorological measurements necessary for agricultural work and several speakers agreed that for some purposes a high degree of accuracy was not necessary. The Director-General closed the meeting which had, he said, shown the diversity of interest in the subject of agricultural meteorology.

OFFICIAL PUBLICATION

The following publication, details of which are given on the back cover, has recently been issued: *Weather in the Mediterranean, Volume* 1, (*Second Edition*), London, HMSO, 1962. Price: 84*s*.

LETTER TO THE EDITOR

Hoar-frost crystals

About 1130 this morning (10 February 1963), I noticed on the pavement (the traditional local brick) on two damp patches some large perfect ice crystals. The road which is at about 340 ft is open to the NE and at one spot to north and east. At this point the crystals were of the usual six rayed type, the rays being clear with what appeared to be indented edges and there was an inner ring of six members; diameter about 15 mm. The other crystal further along the pavement was slightly smaller, the rays thicker and feathery, no inner ring. Both cases were on the NW side of the road. There was some thawing going on in places, but some puddles were slightly iced.

5 *Blatchington Road, Tunbridge Wells, Kent.* CICELY M. BOTLEY

[This is a rare observation. W. A. Bentley, "Studies of frost and crystals", *Monthly Weather Review*, XXXV, 1907, p. 352, remarks that hoar-frost crystals of the type concerned rarely or never develop a perfectly symmetrical plan. A. D. Zamarskij in "*Atmospheric Ice*", *Leningrad*, 1955, p. 35, states that hoar-frost crystals of this type, which constituted 20 per cent of those observed at a point in Leningrad in 1945/1947, do not have a pronounced external regularity.

Ed. M.M.]

OBITUARY

Mr. Feliks Kubicki.—It is with deep regret that we record the death, on 25 February 1963 at the age of 47, of Feliks Kubicki, Senior Scientific Assistant. He was injured when his motor cycle was in collision with another vehicle on 26 January and had been in hospital since the accident without recovering consciousness.

Mr. Kubicki came to this country with many of his Polish compatriots in the early days of the last war and served at a number of RAF stations before returning to civilian life in 1947. He came into radiosonde in 1944 receiving his training at Downham Market, was posted to Fazakerley in 1945 and remained a stalwart of that station until it was transferred to Aughton in 1958. His merited promotion to Senior Scientific Assistant came in 1956. Many assistants and some of the Experimental Officer class will remember with gratitude the practical instruction in radiosonde given them by Feliks, for a great number came to Fazakerley and Aughton for their operational training after the preliminary instruction at the Radiosonde Training School. I am sure they, among many others, will wish to extend their heartfelt sympathy to his widow and three children.

It seems an anomaly that there should be a radiosonde station at Aughton without Feliks Kubicki.

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METEOROLOGICAL OFFICE M.O. 738

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COLD SPELLS AT LONDON

By C. A. S. LOWNDES

Introduction.—This work was undertaken to provide a background to the problem of forecasting the ending of cold spells at London. A cold spell was defined as a period of four or more consecutive days at Kew with the maximum temperature on each day below normal and with the average anomaly of the maximum temperature over the period not less than 3°F (1.7°C). The limiting value of 3°F was chosen because the descriptive terms for cold weather used by the Central Forecasting Office associate anomalies of less than 3°F with average temperatures and only include the words 'cold' or 'cool' in association with anomalies of 3°F or more. (At the time of writing, the use of the Fahrenheit scale is being discontinued in favour of the Celsius scale and the new definition requires a limiting value of 2°C.) The last day of a spell was defined as the day preceding that on which the maximum temperature first rose to normal or above. The graphs published in the *Monthly Summary of the Daily Weather Report* which show maximum temperatures and normal values* for Kew were used to extract the dates of the beginning and end of the spells, and to measure the anomaly of the maximum temperature on each day during the spells. The spells were extracted for the 25-year period 1935 to 1959. Where a spell extended from one month to another it was included in the month which contained the greater part of it. References to anomalies of maximum temperature throughout this paper refer to negative anomalies.

The frequency of cold spells of four days or more.—There were 356 spells during the whole period, giving an average of 1.2 spells per month. Figure 1 shows the average number of spells for each individual month, ranging from 1.0 in February, September and November to 1.6 in May and July. The average monthly range of daily maximum temperature, for the same period, is also shown for comparison. The general similarity of the two curves suggests that for most months the number of spells is related to the range of maximum temperature. The main difference between the curves is associated with July in which the number of spells appears to be higher than the range of tempera-

*Note—For the years 1935 to 1936 the normal values were based on the period 1901 to 1930, for the years 1937 to 1952 on the period 1906 to 1935, and for the years 1953 to 1959 on the period 1921 to 1950.

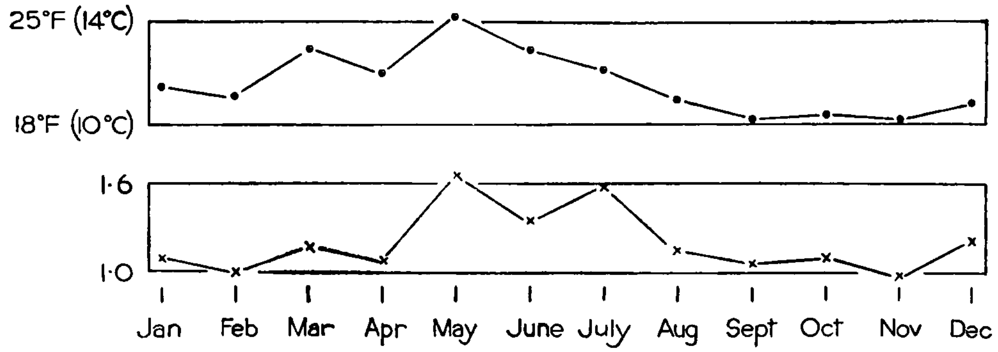

FIGURE I—THE RELATION BETWEEN THE RANGE OF MAXIMUM TEMPERATURE AND THE NUMBER OF SPELLS FOR EACH MONTH

•—•—• average monthly range of maximum temperature
x—x—x average number of spells

ture might suggest. This could be explained by a high proportion of spells in July with small anomalies, but in fact August had more of such spells than July.

Table I shows the number of months unaffected by cold spells, that is months with less than four consecutive cold-spell days.

TABLE I—NUMBER OF MONTHS UNAFFECTED BY COLD SPELLS (IN 25 YEARS)

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
4	4	6	9	4	1	2	4	5	8	9	6

Roughly one in three Aprils, Octobers and Novembers were unaffected by cold spells. On the other hand a cold spell affected nearly every June and July. The number of months unaffected by cold spells in individual years averaged 2.5 and ranged from nil in 1941 and 1956 to five in 1937 and 1949 and seven in 1959.

The frequency of each length of spell is shown in Figure 2. The upper figures at the top of the columns refer to the whole year and those in brackets refer to the six winter months November to April. Of the total spells, 22 per cent were of 4 days, 14 per cent of 5 days and 12 per cent of 6 days, so that nearly half the spells were of 4 to 6 days duration. Spells of 4 to 10 days made up 76 per cent of the total. Of the remainder, 20 per cent were of 11 to 21 days and 4 per cent were 22 days or more in length; the longest spell lasted 56 days. Of the total spells, 55 per cent occurred in the six summer months and 45 per cent in the winter months. The difference was mainly associated with an excess of spells of 6 to 8 days in the summer months. There were 51 spells of 2 weeks or more of which 29 occurred in the winter months. Spells of 3 weeks or more totalled 17 of which 9 occurred in the winter months.

The probability of a cold spell continuing.—The frequency of each length of spell was plotted against the spell-length, a best fitting curve drawn through the points and the frequency corresponding to each length of spell read off from the curve. This procedure was carried out for the six winter and the six summer months. Table II shows the probability values calculated from the frequencies obtained in this way. In the winter months the probability of a cold spell continuing for a further day increases from 0.77 after 4 days to 0.83 after 6 days. After spells of from 7 to 16 days, the probability is roughly

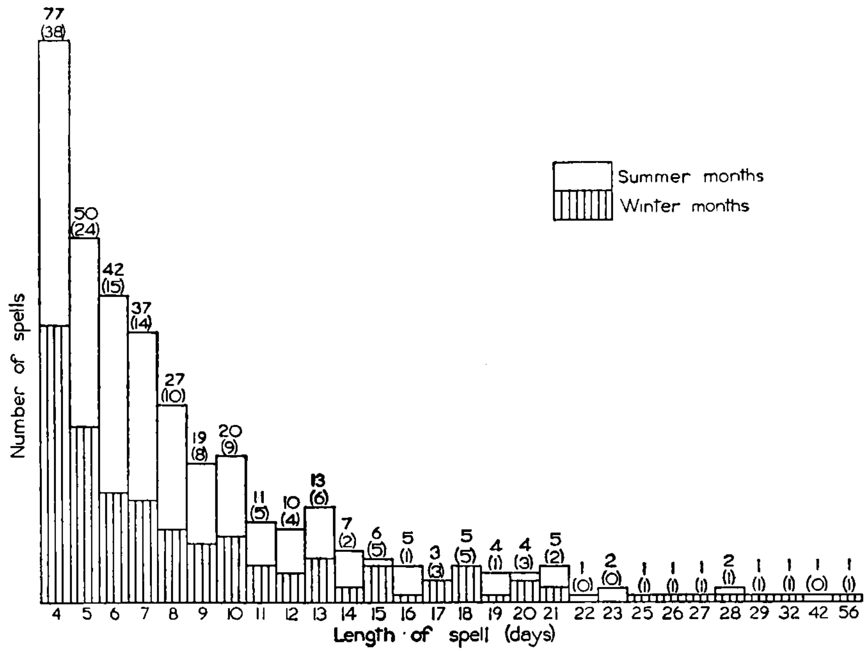

FIGURE 2—FREQUENCY OF EACH LENGTH OF SPELL

Total number of spells — 356, summer months — 194, winter months — 162.
Upper figures at the top of the columns refer to the whole year, figures in brackets to the winter months November to April.

constant at about 0.85. In the summer months, after spells of from 4 to 16 days the probability is roughly constant at about 0.80. There is an even chance that a spell of 4 days will last a further 3 days but in the winter months a spell of 6 days or more has an even chance of lasting a further 4 days.

TABLE II—THE PROBABILITY OF COLD SPELLS OF VARIOUS LENGTHS CONTINUING FOR A FURTHER ONE, TWO, THREE OR FOUR DAYS

(*a*) Six winter months

	Length of cold spell in days							
	4	5	6	7	8	9	10	11
Further day	0.77	0.81	0.83	0.84	0.84	0.85	0.85	0.86
Further 2 days	0.62	0.67	0.70	0.71	0.71	0.72	0.73	0.74
Further 3 days	0.52	0.56	0.59	0.60	0.61	0.62	0.63	0.64
Further 4 days	0.43	0.47	0.50	0.51	0.52	0.53	0.54	0.54

	Length of cold spell in days						
	12	13	14	15	16	17	18
Further day	0.86	0.86	0.85	0.85	0.84	0.83	0.82
Further 2 days	0.74	0.73	0.72	0.71	0.70	0.68	
Further 3 days	0.63	0.62	0.61	0.59	0.57		
Further 4 days	0.53	0.52	0.50	0.49			

(*b*) Six summer months

	Length of cold spell in days							
	4	5	6	7	8	9	10	11
Further day	0.80	0.79	0.79	0.79	0.79	0.80	0.80	0.80
Further 2 days	0.63	0.62	0.62	0.62	0.63	0.64	0.64	0.65
Further 3 days	0.50	0.49	0.49	0.50	0.51	0.51	0.52	0.52
Further 4 days	0.39	0.39	0.39	0.40	0.40	0.41	0.41	0.41

	Length of cold spell in days						
	12	13	14	15	16	17	18
Further day	0.81	0.80	0.80	0.80	0.79	0.78	0.75
Further 2 days	0.65	0.64	0.64	0.63	0.62	0.59	
Further 3 days	0.52	0.51	0.51	0.49	0.46		
Further 4 days	0.41	0.40	0.39	0.37			

It is likely that the relatively high probabilities for the longer spells in the winter months are mainly associated with January and February for which months the average length of spell is much greater than for the other months of the year (see Table X).

The synoptic types associated with cold spells at London.—The classification of the daily weather of the British Isles by Lamb[1] was used to define the synoptic types associated with the cold spells. The classification was made according to the following definitions:

Cyclonic type (*C*).—Depressions stagnating over, or frequently passing across, the British Isles.

Westerly type (*W*).—High pressure to south (also sometimes south-west and south-east) and low pressure to the north of the British Isles. Sequences of depressions and ridges travelling east across the Atlantic.

North-westerly type (*NW*).—Azores anticyclone displaced north-east towards the British Isles or north over the Atlantic west of our coasts, or with extensions in these directions. Depressions (often forming near Iceland) travel south-east or east-south-east into the North Sea and reach their greatest intensity over Scandinavia or the Baltic.

Northerly type (*N*).—High pressure to the west and north-west of the British Isles, particularly over Greenland and sometimes extending as a continuous belt south over the Atlantic Ocean towards the Azores. Low pressure over the Baltic, Scandinavia and the North Sea. Depressions move south or south-east from the Norwegian Sea (sometimes having formed in the Iceland–Jan Mayen region, sometimes having come through from farther north and sometimes having entered the Iceland–Jan Mayen region by way of a col near south Greenland).

Easterly type (*E*).—Anticyclones over, or extending over, Scandinavia and towards Iceland. Depressions circulating over the western North Atlantic and in the Azores–Spain–Biscay region.

Southerly type (*S*).—High pressure covering central and north Europe. Atlantic depressions blocked west of British Isles or travelling north and north-east off our western coasts.

Anticyclonic type (*AC*).—Anticyclones centred over, near, or extending over the British Isles, also cols situated over the country between two anticyclones.

The synoptic type which predominated during each cold spell was noted. The predominant type was taken to be that which occurred on the greatest number of days. If more than one type was equally predominant in this respect, the type which was associated with the greatest anomalies of maximum temperature was taken. Table III shows the number of spells which were predominantly associated with each synoptic type expressed as a percentage of the total number of spells.

TABLE III—THE PERCENTAGE OF COLD SPELLS PREDOMINANTLY ASSOCIATED WITH EACH SYNOPTIC TYPE

	Synoptic type							
	C	*W*	*NW*	*N*	*E*	*S*	*AC*	Total
	percentage of spells							
Six winter months	3	5	1	11	11	4	10	45
Six summer months	13	14	3	12	7	1	5	55
Year	16	19	4	23	18	5	15	100

Over the whole year the highest proportion, some 23 per cent, were northerly-type spells which occurred with about equal frequency in the summer and winter months. Some 19 per cent were westerly-type spells, three-quarters of which occurred in the summer months. A further 18 per cent were easterly-type spells of which two-thirds occurred in the winter months. Of the 16 per cent which were cyclonic-type spells, three-quarters occurred in the summer months. Of the 15 per cent which were anticyclonic-type spells, two-thirds occurred in the winter months. Only about 5 per cent were southerly or north-westerly-type spells.

It is clear that in the winter months the cold spells were mainly associated with the northerly, easterly and anticyclonic types and in the summer months with the westerly, cyclonic and northerly types. Table IV shows the number of cold spells which were predominantly associated with each synoptic type, for each month.

TABLE IV—THE NUMBER OF COLD SPELLS PREDOMINANTLY ASSOCIATED WITH EACH SYNOPTIC TYPE, FOR EACH MONTH (IN 25 YEARS)

Synoptic type	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						number of spells						
C	0	4	2	4	11	9	7	10	5	3	2	1
W	1	2	0	3	1	9	17	13	8	2	5	7
NW	1	0	0	2	2	2	4	1	1	0	0	1
N	9	5	6	9	13	8	6	4	5	7	4	6
E	5	5	15	5	7	3	4	0	1	9•	4	5
S	3	3	2	0	1	1	0	0	0	1	4	3
AC	8	6	4	4	6	1	1	0	6	5	5	7

Cyclonic-type cold spells occurred mainly in the summer months May to August. Westerly-type cold spells were mainly restricted to the months June to September. The number fell sharply from September to October when there was a sharp rise in the number of easterly-type cold spells. May had the highest number of northerly-type cold spells and March the highest number of easterly-type spells. Anticyclonic-type cold spells occurred mainly in the winter months, the number falling sharply from May to June and rising again sharply from August to September.

Table V shows the proportion of days associated with each synoptic type which were part of a cold spell, based on the period 1938 to 1961. The figures represent the probability of a day associated with a particular type being part of a cold spell. The probability is nearly 0.9 for the easterly type in January and February and is about 0.8 for the northerly type in May, August and September and the anticyclonic type in January.

TABLE V—THE PROBABILITY OF A DAY ASSOCIATED WITH A PARTICULAR SYNOPTIC TYPE BEING PART OF A COLD SPELL, 1938–1961

Synoptic type	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						probability						
C	0.26	0.45	0.34	0.32	0.62	0.54	0.57	0.61	0.42	0.16	0.14	0.32
W	0.16	0.10	0.07	0.13	0.25	0.29	0.40	0.41	0.28	0.06	0.12	0.13
NW	0.35	0.32	0.33	0.26	0.55	0.49	0.50	0.62	0.49	0.50	0.22	0.20
N	0.72	0.73	0.62	0.64	0.78	0.65	0.68	0.81	0.80	0.75	0.52	0.59
E	0.86	0.89	0.60	0.57	0.43	0.29	0.44	0.13	0.29	0.51	0.53	0.66
S	0.50	0.25	0.20	0.08	0.14	0.14	0.07	0.12	0.03	0.16	0.13	0.26
AC	0.77	0.63	0.28	0.25	0.28	0.18	0.15	0.17	0.30	0.31	0.50	0.67

The anomalies of daily maximum temperature associated with cold spells at London.—Tables VI to VIII describe the anomalies of daily maximum temperature for cold spells associated with each synoptic type, for each month, to the nearest degree Fahrenheit. Averages based on less than three spells are not included and those based on only three or four spells are shown in brackets.

TABLE VI—THE AVERAGE ANOMALY OF DAILY MAXIMUM TEMPERATURE ASSOCIATED WITH THE COLD SPELLS

Synoptic type	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						degrees Fahrenheit						
C	–	(5)	–	(5)	5	5	4	4	4	(4)	–	–
W	–	–	–	(4)	–	4	5	4	4	–	4	4
NW	–	–	–	–	–	–	(4)	–	–	–	–	–
N	7	6	6	6	7	6	5	(5)	5	5	(6)	6
E	7	11	7	5	5	(5)	(5)	–	–	5	(5)	6
S	(8)	(4)	–	–	–	–	–	–	–	–	(5)	(6)
AC	6	6	(5)	(4)	5	–	–	–	4	5	4	6

Dashes represent occasions on which averages were based on less than three spells and figures in brackets are averages based on only three or four spells.

TABLE VII—THE AVERAGE EXTREME ANOMALY OF DAILY MAXIMUM TEMPERATURE ASSOCIATED WITH THE COLD SPELLS

Synoptic type	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						degrees Fahrenheit						
C	–	(9)	–	(9)	8	9	8	8	6	(7)	–	–
W	–	–	–	(7)	–	7	9	7	7	–	7	8
NW	–	–	–	–	–	–	(6)	–	–	–	–	–
N	10	12	10	10	11	12	9	(10)	9	8	(11)	9
E	12	16	11	9	9	(9)	(11)	–	–	8	(8)	11
S	(15)	(9)	–	–	–	–	–	–	–	–	(8)	(9)
AC	11	10	(8)	(8)	9	–	–	–	8	7	7	11

Dashes represent occasions on which averages were based on less than three spells and figures in brackets are averages based on only three or four spells.

TABLE VIII—THE ABSOLUTE EXTREME ANOMALY OF DAILY MAXIMUM TEMPERATURE ASSOCIATED WITH THE COLD SPELLS

Synoptic type	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						degrees Fahrenheit						
C	–	(15)	–	(11)	12	15	13	13	9	(10)	–	–
W	–	–	–	(9)	–	9	12	10	10	–	9	16
NW	–	–	–	–	–	–	(7)	–	–	–	–	–
N	17	15	13	13	14	16	13	(14)	14	10	(13)	12
E	18	21	18	13	13	(12)	(13)	(5)	–	11	(14)	16
S	(18)	(12)	–	–	–	–	–	–	–	–	(11)	(12)
AC	16	16	(11)	(9)	13	–	–	–	10	9	10	16

Dashes represent occasions on which averages were based on less than three spells and figures in brackets are averages based on only three or four spells.

Table IX shows the number of spells in each month with the average anomaly of the daily maximum temperature within certain limits, expressed as a percentage of the total number of spells in each month.

TABLE IX—THE PERCENTAGE OF SPELLS IN EACH MONTH (IN 25 YEARS) WITH THE AVERAGE ANOMALY OF THE DAILY MAXIMUM TEMPERATURE WITHIN CERTAIN LIMITS

Average anomaly	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						percentage of spells						
3°–6°F (1.4°–3.6°C)	63	56	62	89	71	88	90	96	88	93	83	73
7°–10°F (3.7°–5.8°C)	30	32	38	11	29	12	10	4	12	7	17	27
$>$ 10°F (5.8°C)	7	12										
Total number of spells	27	25	29	27	41	33	39	28	26	27	24	30

The length of the cold spells.—The average length of the cold spells and the duration of the longest spell which occurred in each month are shown in Table X.

TABLE X—THE AVERAGE AND MAXIMUM LENGTH OF SPELLS FOR EACH MONTH (IN 25 YEARS)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						days						
Average length	12	13	7	8	7	8	9	9	9	8	7	8
Maximum length	27	56	20	18	16	23	22	42	28	23	29	26

The average length was 13 days in February and 12 in January. Over the rest of the year it varied from 7 to 9 days. The maximum length of spell varied from 56 days for February to 16 days for May. The two longest spells of 56 and 42 days were centred on February and August respectively. The former extended over the period 19 January to 15 March 1947, the latter over the period 28 July to 7 September 1956, but the end of the spell was temporary and further cold spells occurred over the periods 9–12 and 15–18 September so that the spell could be said to have lasted a further 11 days, totalling 53 days.

The relation between the extreme anomaly and the length of spell.—Figure 3 shows the relation between the extreme anomaly and the average length of spell for the six winter and six summer months. For anomalies of up to 11°F (6°C) the length of spell was greater in the summer months, particularly for anomalies of 6° to 7°F (3° to 4°C). For anomalies above 11°F (6°C) the length of spell was greater in the winter months.

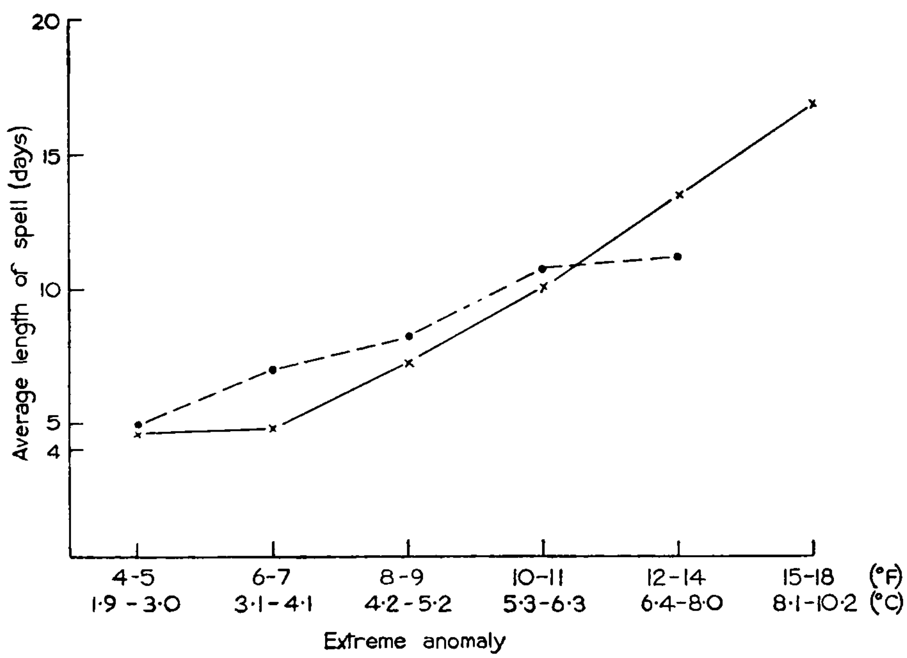

FIGURE 3—THE RELATION BETWEEN THE EXTREME ANOMALY AND THE AVERAGE LENGTH OF SPELL FOR THE SIX SUMMER AND SIX WINTER MONTHS

·— —·— —· summer months x—x—x winter months

The same graph for the winter months only is shown in Figure 4, with the upper and lower tenpercentile limits of the length of spell indicated by pecked lines. On 90 per cent of occasions in the winter months, a spell with an anomaly

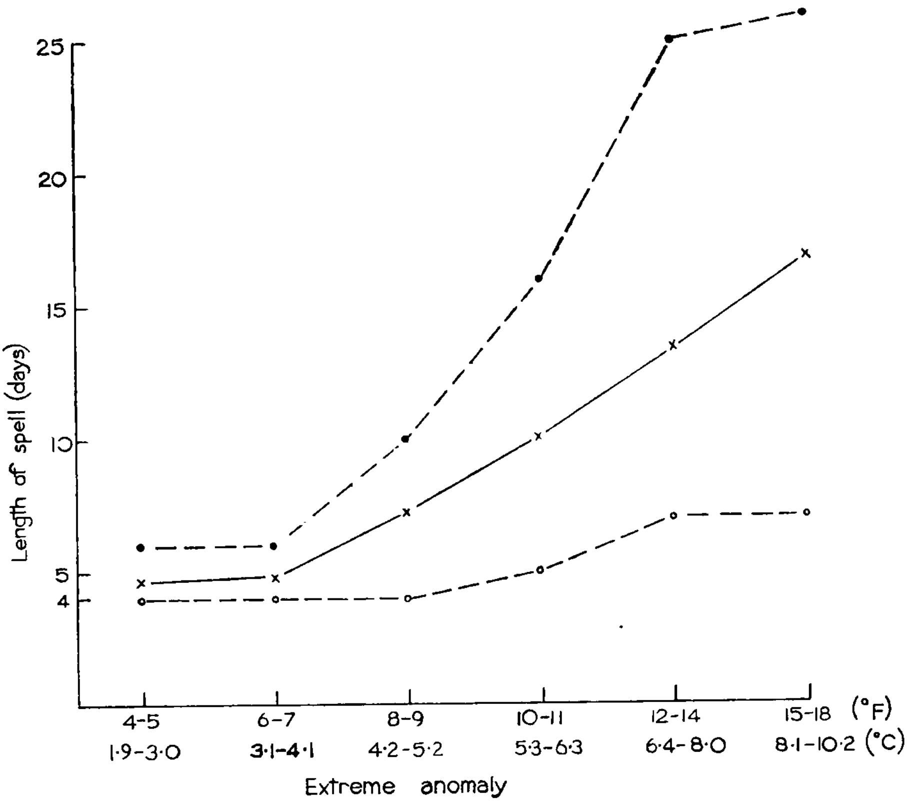

FIGURE 4—THE RELATION BETWEEN THE EXTREME ANOMALY AND THE LENGTH OF SPELL FOR THE SIX WINTER MONTHS

· — — · — — · upper tenpercentile limit   x—x—x average length
o– –o– –o lower tenpercentile limit

of 10°F (6°C) or more lasted for at least 5 days and a spell with an anomaly of 12°F (7°C) or more for at least 7 days. A similar graph for the summer months is shown in Figure 5. On 90 per cent of occasions in the summer months, a spell with an anomaly of 10°F (6°C) or more lasted for at least 6 days.

The incidence of cold-spell days.—Table XI shows the number of cold-spell days expressed as a percentage of the total days for each month and also the average number of cold-spell days for each month.

TABLE XI—THE PERCENTAGE AND AVERAGE NUMBER OF COLD-SPELL DAYS FOR EACH MONTH (IN 25 YEARS)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Percentage	42	41	30	29	38	37	40	35	31	24	24	32
Average number	13	12	9	9	12	11	12	11	9	7	7	10

January, February and July each had about 40 per cent of cold-spell days whilst May, June and August had between 35 and 38 per cent. October and November had the lowest proportion of 24 per cent. The average number of cold-spell days ranged from 7 in October and November to 11–13 in January, February, May, June, July and August.

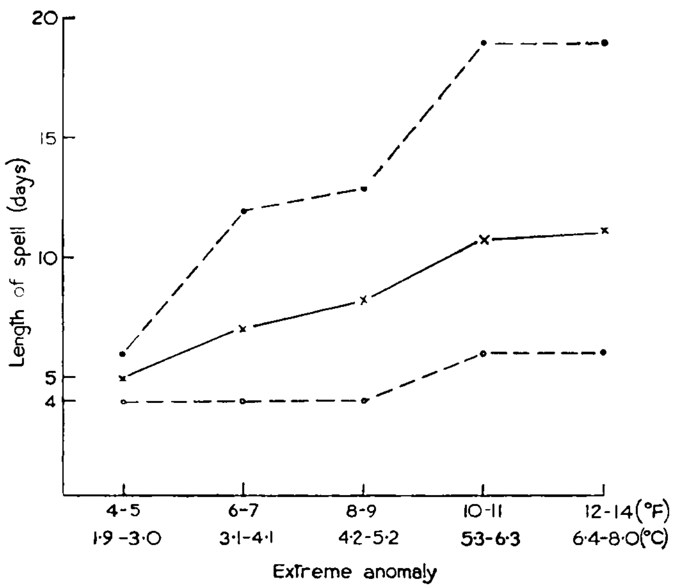

FIGURE 5—THE RELATION BETWEEN THE EXTREME ANOMALY AND THE LENGTH OF SPELL FOR THE SIX SUMMER MONTHS

· — — · — — · upper tenpercentile limit   x—x—x average length
o— —o— —o lower tenpercentile limit

Figure 6 shows the percentage of cold-spell days for each month and the average monthly range of daily maximum temperature for comparison. The curves show some similarity from March to December but the maximum percentage in these months occurred in July whilst the maximum range occurred in May. The curves are quite dissimilar for January and February in which months the range was relatively small but the percentage of cold-spell days was at a maximum. The high percentage of cold-spell days in January and February is clearly associated with the much higher average length of spell in these two months compared with the rest of the year.

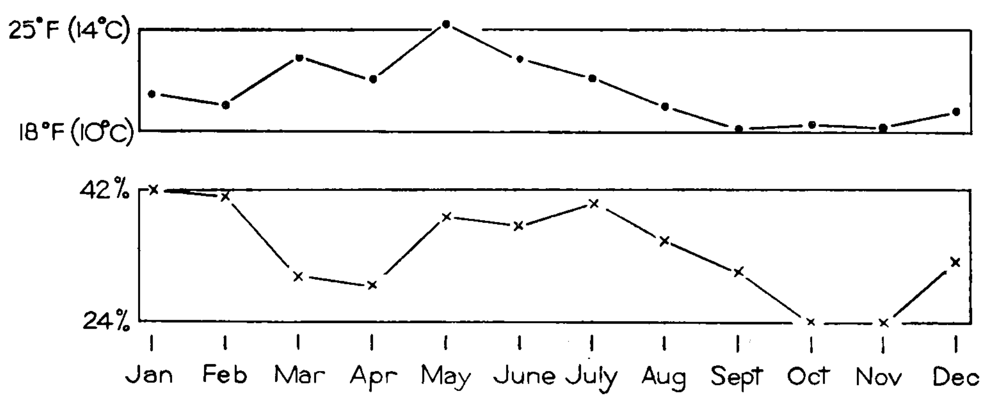

FIGURE 6—THE RELATION BETWEEN THE RANGE OF MAXIMUM TEMPERATURE AND THE PERCENTAGE OF COLD-SPELL DAYS FOR EACH MONTH

· — — · — — · average monthly range of maximum temperature
x—x—x percentage of cold-spell days

The ending of the cold spells.—Table XII shows the number of occasions on which the day after the end of the spell was associated with each synoptic type, expressed as a percentage of the total number of spells during the periods described.

TABLE XII—THE SYNOPTIC TYPE ON THE DAY AFTER THE END OF THE COLD SPELL

	Synoptic type								Total
	C	*W*	*NW*	*N*	*E*	*S*	*AC*	*U*	spells
	percentage of spells								
Six winter months	12	36	7	4	7	19	6	9	162
Six summer months	13	36	4	3	5	17	15	7	194
Year	12	36	6	3	6	18	11	8	356

U indicates occasions when the weather over the British Isles was not classifiable according to any of the seven types.

Over the whole year, 36 per cent of the spells ended with the westerly type and 18 per cent with the southerly type. About 10 per cent ended with the cyclonic and anticyclonic types. There was little difference between the winter and summer halves of the year, but most of the anticyclonic-type endings occurred in the summer months. The ending of 24 per cent of the spells was temporary, that is a further cold spell began during the 4 days following the last day of the spell. Of these spells 61 per cent occurred in the summer half of the year.

Table XIII shows the number of cold spells associated with each synoptic type which had a temporary ending, for the six winter and six summer months.

TABLE XIII—THE NUMBER OF COLD SPELLS WITH A TEMPORARY ENDING

(*a*) Six winter months

	Predominant synoptic type						
	C	*W*	*NW*	*N*	*E*	*S*	*AC*
	number of spells						
With temporary ending	3	2	1	4	13	2	10
Total spells	13	18	4	39	39	15	34

(*b*) Six summer months

	Predominant synoptic type						
	C	*W*	*NW*	*N*	*E*	*S*	*AC*
	number of spells						
With temporary ending	12	17	2	12	6	0	3
Total spells	45	50	10	43	24	3	19

In the winter months only 10 per cent of northerly-type spells, 11 per cent of westerly-type spells and 13 per cent of southerly-type spells had a temporary ending. In the summer months, only 16 per cent of anticyclonic-type spells had a temporary ending.

Table XIV is in two parts (*a*) and (*b*) according to season. The main figures demonstrate the number of occasions when the ending of the spell was permanent and are classified according to the synoptic type during the spell and the type just after the spell. The figures in brackets show how often the ending was temporary.

There is a suggestion that spells with certain characteristics are unlikely to have a temporary ending; e.g. in the winter months westerly- and northerly-type spells with a westerly-type ending, and in the summer months northerly-type spells with a southerly-type ending.

TABLE XIV—THE ASSOCIATION BETWEEN THE SYNOPTIC TYPE ON THE DAY AFTER THE END OF THE COLD SPELL AND THE PERMANENCE OF THE ENDING

(*a*) Six winter months

Predominant synoptic type during spell	Synoptic type on day after end of spell *C*	*W*	*NW*	*N*	*E*	*S*	*AC*	*U*
	number of occasions							
C	1 (1)	4 (1)	0 (1)	–	–	3 (0)	1 (0)	1 (0)
W	1 (0)	11 (1)	–	1 (0)	1 (0)	2 (0)	–	0 (1)
NW	–	0 (1)	2 (0)	–	–	–	–	1 (0)
N	7 (1)	15 (0)	2 (1)	1 (1)	0 (1)	6 (0)	1 (0)	3 (0)
E	3 (2)	9 (3)	2 (1)	1 (0)	3 (3)	6 (1)	–	2 (2)
S	1 (1)	2 (1)	–	–	2 (0)	6 (0)	–	2 (0)
AC	1 (0)	8 (3)	2 (1)	1 (1)	1 (0)	3 (4)	6 (1)	2 (0)

(*b*) Six summer months

Predominant synoptic type during spell	Synoptic type on day after end of spell *C*	*W*	*NW*	*N*	*E*	*S*	*AC*	*U*
	number of occasions							
C	10 (3)	11 (3)	1 (0)	–	1 (1)	5 (3)	3 (0)	2 (2)
W	2 (3)	18 (12)	1 (0)	1 (0)	–	2 (0)	6 (1)	3 (1)
NW	1 (1)	3 (0)	2 (0)	–	–	1 (0)	1 (1)	–
N	2 (1)	7 (2)	2 (0)	0 (2)	2 (1)	10 (0)	6 (5)	2 (1)
E	1 (0)	7 (1)	–	0 (2)	3 (1)	6 (1)	1 (0)	0 (1)
S	–	3 (0)	–	–	–	–	–	–
AC	1 (0)	3 (1)	1 (1)	–	1 (0)	4 (1)	5 (0)	1 (0)

U—occasions when the weather on the day after the end of a spell was not classifiable according to any of the seven types. The first figure represents the number of occasions when the ending of a spell was permanent, and the figure in brackets the occasions when the ending was temporary.

The period between the end of a cold spell and the beginning of the next.—Figure 7 shows the average period between cold spells and also the upper and lower tenpercentile limits of the period, for each month. The average period ranged from a minimum of 10 days in May to a maximum of

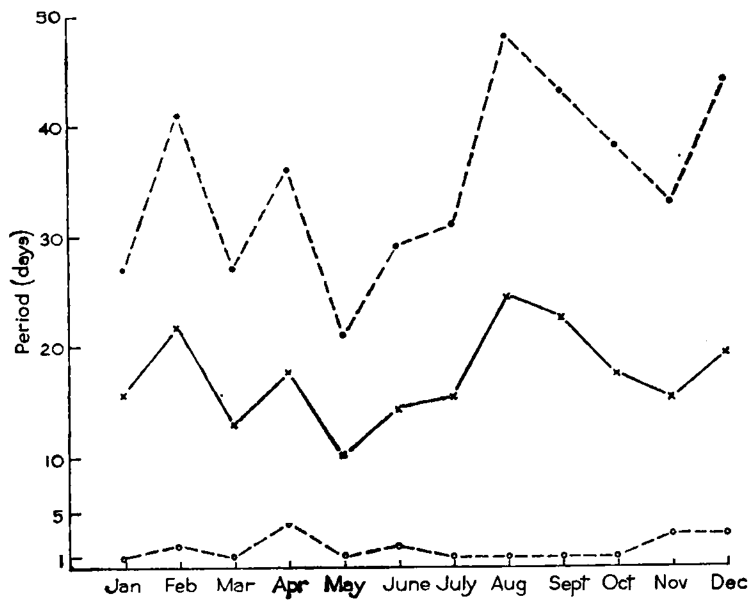

FIGURE 7—THE PERIOD BETWEEN THE END OF A COLD SPELL AND THE BEGINNING OF THE NEXT

– –.– –. upper tenpercentile limit x—x—x average
o– –o– –o lower tenpercentile limit

24 days in August. On 90 per cent of occasions in April the period was of at least 4 days and in November and December of at least 3 days. The longest period of 156 days occurred after a spell which ended in August.

Conclusions.—In the 25-year period 1935 to 1959, cold spells of 4 days or more, as defined in this paper, averaged just over one per month. Roughly one in three Aprils, Octobers and Novembers were unaffected by cold spells but a cold spell affected nearly every June and July. The number of months unaffected by cold spells in individual years ranged from nil in 1941 and 1956 to seven in 1959. Some 76 per cent of the spells were of 4 to 10 days in length and the longest spell lasted 56 days. The probability of a cold spell continuing for a further day is roughly constant at about 0.8 for spells of up to 18 days duration.

The highest proportion of cold spells, some 23 per cent, were predominantly associated with the northerly synoptic type. In the winter months the spells were mainly associated with the northerly, easterly and anticyclonic types and in the summer months with the westerly, cyclonic and northerly types. About half the spells in March were predominantly associated with the easterly type and just under half the spells in July and August with the westerly type.

The probability of a cold spell is particularly high with the easterly type in January and February, the northerly type in May, August and September and the anticyclonic type in January.

The largest average anomaly of daily maximum temperature of 11°F (6°C) was associated with easterly-type cold spells in February. Westerly-type cold spells were the least cold with an average anomaly of 4°F (2°C) or less in most months. The largest average extreme anomaly of 15° to 16°F (8° to 9°C) was associated with easterly-type cold spells in February and southerly-type cold spells in January. The largest absolute extreme anomaly of 21°F (12°C) was associated with an easterly-type cold spell in February. The month which was least affected by very cold days was October with an absolute extreme anomaly of 11°F (6°C).

The average length of spell for January and February was 12 to 13 days, much higher than for the rest of the year when it varied from 7 to 9 days. On 90 per cent of occasions, in the winter months, a cold spell with an extreme anomaly of 10°F (6°C) or more lasted for at least 5 days, and with an anomaly of 12°F (7°C) or more for at least 7 days. In the summer months a spell with an anomaly of 10°F (6°C) or more lasted for at least 6 days.

The average number of cold-spell days for each month ranged from 7 in October and November to 11 to 13 in January, February, May, June, July and August.

Some 24 per cent of the cold spells had a temporary ending, but in the winter months only about 10 per cent of northerly- and westerly-type cold spells had a temporary ending. There is a suggestion that cold spells with certain characteristics are unlikely to have a temporary ending, in particular, westerly- and northerly-type cold spells with a westerly-type ending in the winter months and northerly-type cold spells with a southerly-type ending in the summer months.

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A STUDY OF PERSISTENT AND SEMI-PERSISTENT THICK AND DENSE FOG IN THE LONDON AREA DURING THE DECADE 1947–56

By T. KELLY, B.Sc.

Introduction.—The three stations used in this study were London (Heathrow) Airport, Croydon Airport and Kingsway. The information required for Heathrow had already been extracted for the period 1949–56 and was supplied by the Meteorological Office, Bracknell. The Chief Meteorological Officer, London (Heathrow) Airport, provided that for the two years 1947 and 1948. The information for Croydon and Kingsway was extracted from the original daily registers.

Following normal Meteorological Office practice, persistent fog is taken to mean fog which lasts for 24 hours or more. For the purpose of this study, semi-persistent fog is defined as fog which lasts for 12 hours or more and therefore includes all occasions of persistent fog. Dense fog is defined as visibility less than 55 yards (as is customary in connexion with the public), and thick fog less than 220 yards, and therefore, all occasions of dense fog will be included in the statistics for thick fog.

All cases of persistent and semi-persistent thick and dense fog during the period are given for the three stations in Table I and Table II. For Heathrow and Croydon, hourly observations were used to estimate the lengths of the foggy periods, each hourly observation being assumed to represent one hour of fog. In the Heathrow and Croydon data a sequence of hourly observations of fog was regarded as being unbroken if the visibility had risen above the prescribed limits at a single hourly observation only, in an otherwise continuous sequence. There was, in fact, a break of one single hour in seven cases at Heathrow and six at Croydon. At Kingsway, observations were available only at 3-hourly intervals and the assumption was made that each observation of fog represented 3 hours of fog, as assumed by Shellard.[1] Objection may be made to this but, in order to determine the validity of the assumption, estimates of persistent and semi-persistent thick and dense fog at Croydon were derived from 3-hourly observations and these were compared with those based on hourly observations. Inspection of columns 5, 6, 7 and 8 in Table I shows that the agreement between the two sets of information is good. There were three instances when the 3-hourly observations gave semi-persistent thick fog not given by the hourly observations and one instance when the hourly observations gave semi-persistent thick fog not given by the 3-hourly observations, the periods which lasted for less than 12 hours being given in brackets. The outstanding discrepancies between columns 5 and 7 of Table I took place on 25–26 November 1950, when the visibility was 300 yards at midnight, thus breaking the sequence of 3-hourly observations but not that of the hourly observations, and on 19–20 January 1953, when the visibility was not less than 220 yards at 1300 and 1400 GMT on the 19th, thus breaking the hourly sequence but not the 3-hourly sequence. In Table I the number of occasions of persistent and semi-persistent thick fog at Croydon based on hourly observations was 24 compared with 26 based on 3-hourly observations, and the total number of hours was 414 based on hourly observations compared with 432 based on 3-

TABLE I—PERIODS OF PERSISTENT AND SEMI-PERSISTENT THICK FOG IN THE LONDON AREA

		Heathrow (hourly)		Croydon (hourly)		Croydon (3-hourly)		Kingsway (3-hourly)	
1	2	3	4	5	6	7	8	9	10
Year	Month	Period observed	Estimated duration	Period observed	Estimated duration	Period observed	Estimated duration	Period observed	Estimated duration
		date/time (GMT)	*hours*	*date/time* (GMT)	*hours*	*date/time* (GMT)	*hours*	*date/time* (GMT)	*hours*
1947	Jan.	07/2300 – 08/1000	12						
	Feb.							09/1800 – 10/0900	18
	Nov.	05/2300 – 06/1200	14	06/0100 – 06/1600	16	06/0300 – 06/1500	15	06/0600 – 07/0600	27
	Nov.	06/1600 – 07/0800	17						
	Nov.	30/2100 – 01/1800	22						
1948	Mar.	02/2100 – 03/1100	15	(02/2100 – 03/0600	10)	02/2100 – 03/0600	12		
	Mar.			05/2000 – 06/1000	15	05/2100 – 06/0900	15		
	Mar.							06/1500 – 06/2400	12
	Oct.			30/2000 – 31/0700	12	30/2100 – 31/0600	12		
	Nov.	11/0900 – 12/1000	14						
	Nov.			23/2000 – 24/0900	14	23/2100 – 24/0900	15		
	Nov.	27/0900 – 29/1000	50	27/2100 – 29/0600	34	27/2100 – 29/0600	36	27/1800 – 28/0900	18
	Nov.							28/1500 – 29/0900	21
	Nov.	30/0100		29/1400		29/1500		30/1500	
	Dec.	– 01/1400	38	– 01/0900	44	– 01/0900	45	– 01/1200	24
	Dec.	25/1900 – 26/1100	29	26/0700 – 26/1900	13	26/0900 – 26/1800	12		
1949	Jan.	28/0200 – 28/1500	14						
	Jan.	29/0900 – 30/0300	19						
	Jan.			30/1300 – 30/2400	12	(30/1800 – 30/2400	9)		
	Nov.	15/0200 – 15/1800	15						
	Nov.	18/2000 – 19/1700	22						
1950	Jan.	26/2000 – 28/1300	30						
	Nov.	25/0700 – 25/1900	13	25/1500 – 26/0900	19	25/1200 – 25/2100	12		
	Nov.	26/0700 – 27/0900	27	26/1600 – 27/0800	17	26/1800 – 27/0600	15	26/1200 – 27/0600	21
1951	Jan.	29/2000 – 30/1100	16	29/0700 – 30/0500	23	29/0900 – 30/0300	21		
	Oct.			15/0000 – 15/1100	12	15/0000 – 15/0900	12		
	Oct.	15/2200 – 16/1100	14	15/2200 – 16/0900	12	16/0000 – 16/0900	12		
	Dec.	13/1800 – 14/1100	18					13/2100 – 14/0900	15

TABLE I—PERIODS OF PERSISTENT AND SEMI-PERSISTENT THICK FOG IN THE LONDON AREA—*continued*

		Heathrow (hourly)		Croydon (hourly)		Croydon (3-hourly)		Kingsway (3-hourly)	
1 Year	2 Month	3 Period observed	4 Estimated duration	5 Period observed	6 Estimated duration	7 Period observed	8 Estimated duration	9 Period observed	10 Estimated duration
		date/time (GMT)	*hours*	*date/time* (GMT)	*hours*	*date/time* (GMT)	*hours*	*date/time* (GMT)	*hours*
1952	Feb.			(28/0000 – 28/1000	11)	28/0000 – 28/0900	12		
	Dec.	05/1600 – 08/1200	69	(07/0300 – 07/1300	11)	07/0300 – 07/1200	12	06/0900 – 08/0900	51
	Dec.							08/1800 – 09/0300	12
	Dec.			27/0400 – 27/1600	13	27/0600 – 27/1500	12		
1953	Jan.	19/0600 – 20/1100	30	19/1500 – 20/0300	13	19/0900 – 20/0300	21		
	Mar.	02/2100 – 03/0900	13	02/2000 – 03/1000	15	02/2100 – 03/0900	15		
	Mar.			03/2100 – 04/0900	13	03/2100 – 04/0900	15		
	Nov.	17/0000 – 17/1200	13						
	Nov.	25/1600 – 26/0400	13						
	Dec.	17/2200 – 18/1800	21	17/2300 – 18/1300	15	18/0000 – 18/1200	15	18/0300 – 18/1500	15
	Dec.	20/2100 – 21/0900	13						
1954	Nov.	17/2200 – 18/1200	15	17/2200 – 18/1100	14	18/0000 – 18/0900	12		
	Nov.	19/2000 – 20/0900	14						
1955	Jan.	21/1600 – 22/0900	18						
	Oct.	11/2000 – 12/1100	16						
	Nov.			30/0400 – 30/1600	13	30/0600 – 30/1500	12		
	Dec.	01/1800 – 02/1100	18						
1956	Jan.	04/0800 – 06/1100	52	05/0500 – 06/0900	29	05/0600 – 06/0900	30	05/0600 – 06/0900	30
	Nov.			22/2200 – 23/0900	12	23/0000 – 23/0900	12		
	Dec.	08/2300 – 09/2200	24						
	Dec.			19/0400 – 19/1700	14	19/0600 – 19/1500	12	19/0300 – 20/0300	27
	Dec.	20/0100 – 20/2400	24	20/0100 – 20/2000	20	20/0300 – 20/1800	18		

TABLE II—PERIODS OF PERSISTENT AND SEMI-PERSISTENT DENSE FOG IN THE LONDON AREA

		Heathrow (hourly)		Croydon (hourly)		Croydon (3-hourly)		Kingsway (3-hourly)	
1 Year	2 Month	3 Period observed	4 Estimated duration	5 Period observed	6 Estimated duration	7 Period observed	8 Estimated duration	9 Period observed	10 Estimated duration
		date/time (GMT)	*hours*	*date/time* (GMT)	*hours*	*date/time* (GMT)	*hours*	*date/time* (GMT)	*hours*
1947	Nov.	06/1600 – 07/0400	13					06/1200 – 07/0600	21
1948	Nov.	27/1400 – 28/0400	15	27/2100 – 29/0500	32	27/2100 – 28/0600	12		
	Nov.					28/1200 – 29/0300	18		
	Nov.			30/0800		30/0900		30/1500	
	Dec.			– 01/0900	26	– 01/0300	21	– 01/1200	24
1949	Jan.	29/1300 – 29/2400	12						
1950	Nov.	26/1600 – 27/0400	13						
1951		Nil							
1952	Dec.	06/0100 – 07/1300	37					06/0900 – 08/0300	45
1953	Mar.			02/2200 – 03/0900	12	03/0000 – 03/0900	12		
1954		Nil							
1955		Nil							
1956	Jan.	04/1400 – 05/0200	13						
	Jan.	05/0500 – 06/0300	23	05/1800 – 06/0500	12	05/1800 – 06/0300	12		
	Dec.							19/0600 – 19/1500	12

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PLATE I—'BOAT DRILL', WINNING PHOTOGRAPH IN THE 1961 SEAFARERS' EDUCATION SERVICE COMPETITION

See page 195

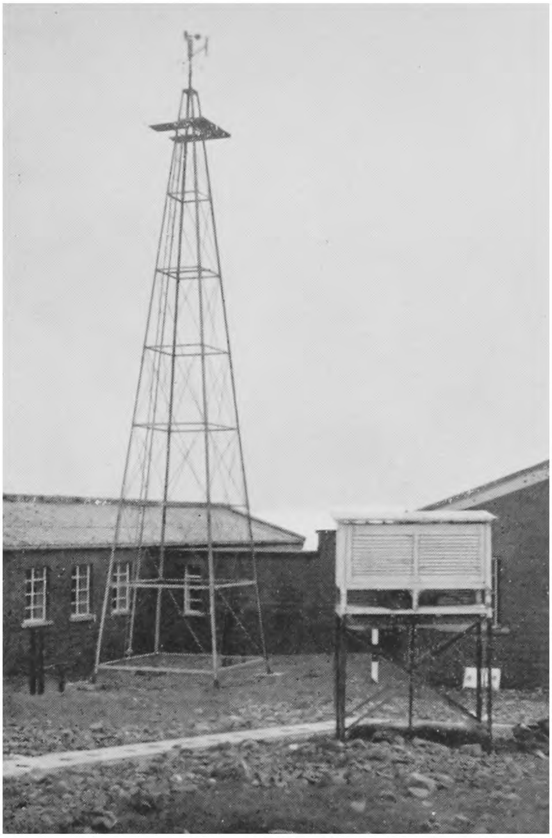

PLATE II—THERMOMETER SCREEN AND ELECTRICAL ANEMOMETER MAST AT LOWTHER HILL

The electrical anemometer, which has a 'standard' exposure, was brought into use in July 1961.

PLATE III—SUNSHINE RECORDER AT LOWTHER HILL

This view looking E'S indicates the nature of the site which is 2377 feet above sea level.

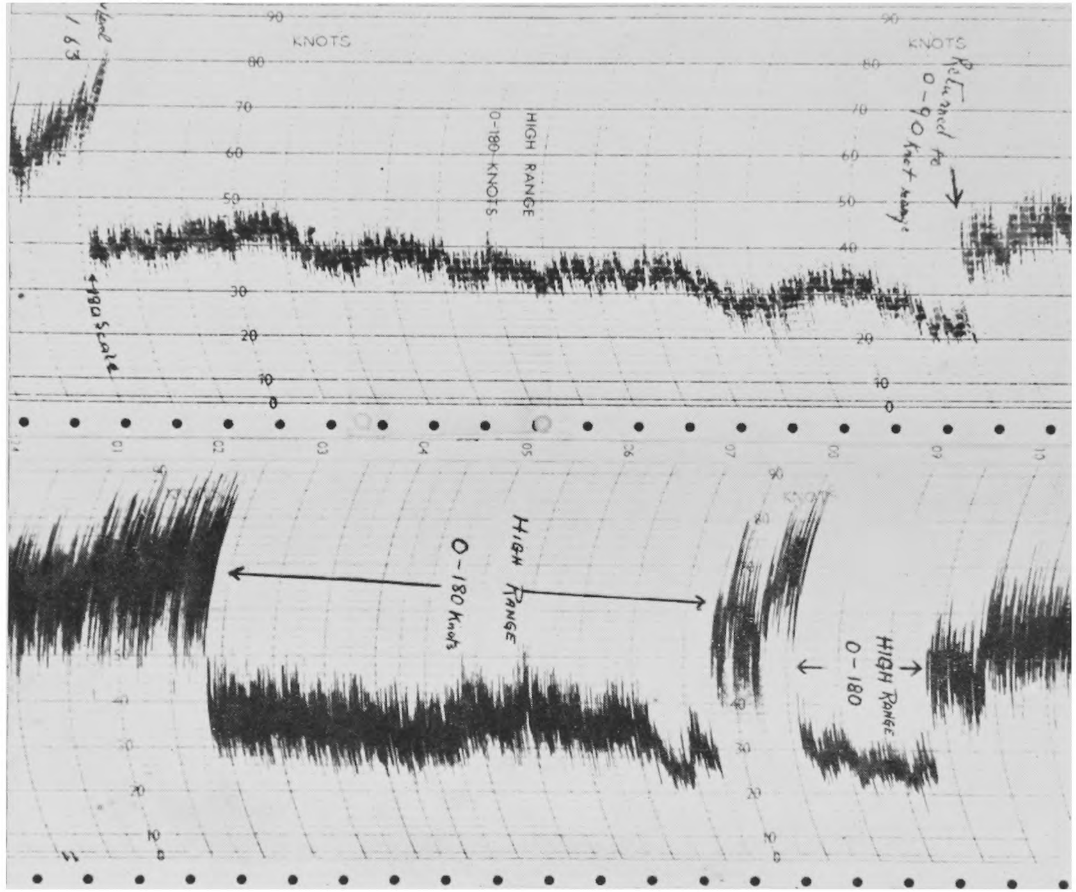

PLATE IV—ANEMOGRAMS FROM THE ELECTRICAL ANEMOMETER AT LOWTHER HILL, LANARKSHIRE SHOWING THE HIGHEST MEAN HOURLY WIND AND THE HIGHEST GUST EVER RECORDED ON AN ANEMOMETER WITH 'STANDARD' EXPOSURE

The upper chart shows the highest mean hourly wind of 86 knots recorded on 20 January 1963, the lower chart the highest gust of 106 knots on 12 February 1962. Note the change from one scale to another when the wind reaches a certain speed.

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PLATE V—TIME-LAPSE CINE-CAMERA IN USE AT THE METEOROLOGICAL OFFICE TRAINING SCHOOL

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hourly observations. Thus the error introduced by using the 3-hourly observations seems to be of the order of an over-estimation of about 8 per cent in the number of occasions of semi-persistent thick fog and about 4 per cent in the total number of hours. In Table II columns 5 and 7 would have been almost identical but for the fact that the visibility was not less than 55 yards at 0900 GMT on 28 November 1948, and again on 1 December 1948, thus breaking the 3-hourly sequence but not the hourly sequence each time. It is, therefore, reasonable to assume that the information based on 3-hourly observations at Kingsway can be compared directly with that derived from hourly observations at Heathrow and Croydon.

Discussion.

(*a*) *Thick fog*.—Tables III, IV and V are extracted from Table I and show the number of occasions and the total duration, month by month, of semi-persistent thick fog at Heathrow, Croydon and Kingsway respectively. A comparison of these tables shows that the frequency of semi-persistent thick fog is highest at Heathrow and lowest at Kingsway. In fact, over the period considered, semi-persistent thick fog occurred in the ratios: Heathrow : Croydon : Kingsway = 34 : 24 : 13 = 3 : 2 : 1 (approximately). At Heathrow and Croydon semi-persistent thick fog was observed during the months October to January inclusive, and also in March. It was most frequent in November and did not occur at all in February. At Kingsway October was free from semi-persistent thick fog but there were five cases in both November and December and one in each of the months January, February and March. Of the 13 occurrences of semi-persistent thick fog at Kingsway only three

TABLE III—NUMBER OF OCCASIONS AND TOTAL NUMBER OF HOURS OF PERSISTENT AND SEMI-PERSISTENT THICK FOG AT HEATHROW

Year	Jan.	Feb.	Mar.	Oct.	Nov.	Dec.	Yearly total
1947	1 (12)				3 (53)		6 (65)
1948			1 (15)		3 (105)	1 (29)	5 (149)
1949	2 (33)				2 (37)		4 (70)
1950	1 (30)				2 (40)		3 (70)
1951	1 (16)			1 (14)		1 (18)	3 (48)
1952						1 (69)	1 (69)
1953	1 (30)		1 (13)		2 (26)	2 (34)	6 (103)
1954					2 (29)		2 (29)
1955	1 (18)			1 (16)		1 (18)	3 (52)
1956	1 (52)					2 (48)	3 (100)
Total	8 (191)		2 (28)	2 (30)	14 (290)	8 (216)	34 (755)

First figure is number of occasions, figures in brackets are total number of hours.

TABLE IV—NUMBER OF OCCASIONS AND TOTAL NUMBER OF HOURS OF PERSISTENT AND SEMI-PERSISTENT THICK FOG AT CROYDON

Year	Jan.	Feb.	Mar.	Oct.	Nov.	Dec.	Yearly total
1947					1 (16)		1 (16)
1948			1 (15)	1 (12)	2 (48)	2 (57)	6 (132)
1949	1 (12)						1 (12)
1950					2 (36)		2 (36)
1951	1 (23)			2 (24)			3 (47)
1952						1 (13)	1 (13)
1953	1 (13)		2 (28)			1 (15)	4 (56)
1954					1 (14)		1 (14)
1955					1 (13)		1 (13)
1956	1 (29)				1 (12)	2 (34)	4 (75)
Total	4 (77)		3 (43)	3 (36)	8 (139)	6 (119)	24 (414)

First figure is number of occasions, figures in brackets are total number of hours.

TABLE V—NUMBER OF OCCASIONS AND TOTAL NUMBER OF HOURS OF PERSISTENT AND SEMI-PERSISTENT THICK FOG AT KINGSWAY

Year	Jan.	Feb.	Mar.	Oct.	Nov.	Dec.	Yearly total
1947		1 (18)			1 (27)		2 (45)
1948			1 (12)		3 (63)		4 (75)
1949							
1950					1 (21)		1 (21)
1951						1 (15)	1 (15)
1952						2 (63)	2 (63)
1953						1 (15)	1 (15)
1954							
1955							
1956	1 (30)					1 (27)	2 (57)
Total	1 (30)	1 (18)	1 (12)		5 (111)	5 (120)	13 (291)

First figure is number of occasions, figures in brackets are total number of hours.

were not accompanied by semi-persistent thick fog at Heathrow and/or Croydon, although on these three occasions thick fog was observed at Heathrow and Croydon but it did not last for 12 hours. From this, it can be concluded that semi-persistent thick fog usually occurs at Kingsway only when thick fog is widespread in the London area. Over the 10-year period considered, the total number of hours of semi-persistent thick fog was: Heathrow : Croydon : Kingsway = 755 : 414 : 291 = 5 : 3 : 2 (approximately).

Table VI gives the dates of the earliest and latest reports of semi-persistent thick fog at each of the three stations. The number of occasions of persistent thick fog was: Heathrow : Croydon : Kingsway = 10 : 3 : 5, showing that the frequency of persistent thick fog was highest at Heathrow and lowest at Croydon.

TABLE VI—EARLIEST AND LATEST OCCURRENCES OF SEMI-PERSISTENT THICK FOG IN THE LONDON AREA

	Earliest occurrence	Duration	Latest occurrence	Duration
Heathrow	15 October 1955	16 hours	2 March 1948	15 hours
Croydon	15 October 1951	12 hours	5 March 1948	15 hours
Kingsway	*6 November 1947	27 hours	6 March 1948	12 hours

*This was also a persistent fog.

The total number of hours of persistent thick fog was: Heathrow : Croydon : Kingsway = 373 : 107 : 159 = 7 : 2 : 3 (approximately). The longest periods of persistent thick fog were 69 hours at Heathrow on 5 December 1952, 44 hours at Croydon on 29 November 1948 and 51 hours at Kingsway on 6 December 1952. The dates of the earliest and latest reports of persistent thick fog at each of the three stations are given in Table VII.

TABLE VII—EARLIEST AND LATEST OCCURRENCES OF PERSISTENT THICK FOG IN THE LONDON AREA

	Earliest occurrence	Duration	Latest occurrence	Duration
Heathrow	26 November 1950	27 hours	26 January 1950	30 hours
Croydon	27 November 1948	34 hours	5 January 1956	29 hours
Kingsway	6 November 1947	27 hours	5 January 1956	30 hours

(*b*) *Dense fog*.—All the cases of persistent and semi-persistent dense fog are listed in Table II. At Heathrow semi-persistent dense fog was reported in November, December and January, at Croydon it was recorded in November, December, January and March while at Kingsway it occurred only during the months of November and December. The number of occasions of semi-persistent dense fog was: Heathrow : Croydon : Kingsway = 7 : 4 : 4. During the period considered, the total number of hours of semi-persistent dense fog was: Heathrow : Croydon : Kingsway = 126 : 82 : 102 = 6 : 4 : 5 (approximately).

During the decade 1947–56 there was only one case of persistent dense fog (37 hours on 6–7 December 1952) at Heathrow, although a dense fog lasted for 23 hours on 5–6 January 1956. Persistent dense fog occurred twice at Croydon (32 hours on 27–29 November 1948 and 26 hours on 30 November–1 December 1948) and twice at Kingsway (24 hours on 30 November–1 December 1948 and 45 hours on 6–8 December 1952). There was, therefore, little difference between the three stations. The longest period of dense fog (dealt with in detail by Douglas and Stewart[2]) was the 45 hours which occurred at Kingsway in December 1952.

Synoptic situation.—An examination was made of the synoptic situation on each occasion of persistent thick fog. In most cases an anticyclone moved slowly across, or in the vicinity of, the British Isles from the Atlantic, but in two instances new anticyclones formed over the British Isles in the slack pressure gradient behind a cold front. Persistent fog also formed in the southerly airstream associated with well-established anticyclones over the continent of Europe.

Conclusions.—Semi-persistent thick fog occurred most frequently at Heathrow and least frequently at Kingsway, while persistent thick fog was most frequent at Heathrow and least frequent at Croydon. Heathrow had almost twice as many semi-persistent dense fogs as Croydon and Kingsway but there was little difference between the three stations when persistent dense fog was considered.

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551.509.317

THE 100 MB CHART AND A CHANGE OF SURFACE WEATHER TYPE NEAR THE BRITISH ISLES

By N. E. DAVIS, M.A.

Investigation of the 100 mb synoptic contour chart has been proceeding at London (Heathrow) Airport for the past two years. The following note reports on a very successful example of the use of the 100 mb chart in forecasting the end of a long spell of cold weather in the United Kingdom. The note presents only a concise account of the chart sequences without attempting to justify them on mathematical or physical grounds.

March 1962 was characterized at Heathrow by a long, cold, mainly dry spell lasting until the 25th, followed by near-normal temperatures in a rather wet cyclonic spell for the last 6 days. Table I shows the mean maximum and minimum temperatures and total rainfall at Heathrow for the first 25 days, the last 6 days and the whole month, compared with the March average for 1947 to 1962.

TABLE I—CHANGE OF SURFACE WEATHER TYPE IN MARCH 1962

	March 1962			March average
	1–25	26–31	1–31	(1947–1962)
		degrees centigrade		
Mean maximum temperature	6.4	10.9	7.3	10.5
Mean minimum temperature	—0.9	2.1	—0.3	2.8
		millimetres		
Rainfall	14.8	20.0	34.8	37.7

This table shows that the temperature for the first 25 days was nearly 4°C below normal (an exceptional departure from the mean) whilst the last 6 days were near normal. The total rainfall was only slightly below the normal of about 38 millimetres but more than half the total precipitation fell during the last 6 days. Table I therefore shows that a very significant change of weather type took place in the vicinity of the British Isles on about 25 March. That such a change was imminent was foreshadowed by the 100 mb contour chart some 4 days earlier.

Figure 1 shows the 100 mb chart for 0001 GMT, 20 March 1962. This chart was typical of the first 20 days of the month. A closed cyclonic circulation was centred between Spitzbergen and Novaja Zemlja with another closed circulation over Canada. The looping track of the second centre is shown by the thick line joining the crosses which mark the position of the centre at 0001 GMT each day from 1 March to 20 March. Between these two centres a ridge persisted over the mid-Atlantic with a surface 'high' in the Greenland–Iceland area (near the top of the upper ridge). The British Isles were, as a consequence, mostly in a cold anticyclonic northerly flow at the surface.

Figure 2 shows the 100 mb chart for 0001 GMT, 21 March; a definite change is in progress. The closed circulation over Labrador has filled up leaving a trough extending southwards over Newfoundland, whilst the ridge over the mid-Atlantic shows definite signs of collapse. The process was even more marked on the 100 mb chart for 0001 GMT, 22 March (Figure 3) which shows quite a westerly flow existing from Greenland to Scotland, compared with the strong ridge of 20 March. It was confidently anticipated at Heathrow that the cold northerlies over the British Isles would be replaced by a cyclonic type of circulation within two or three days—the two or three days time lag being required for a suitable depression to move from the Cape Hatteras (North Carolina) area round the upper trough and thence eastwards to Scotland. Subsequently the trough at 100 mb off Labrador moved westwards, but the Atlantic remained under the influence of the west to west-north-west airstream.

Figure 4 shows the 0001 GMT surface chart for 22 March 1962. A deepening depression is moving eastwards near Cape Hatteras and a stationary 'high' is centred near ocean weather station Alpha (62°N, 33°W). Twenty-four hours later (Figure 5) the depression has moved eastwards to a position between Bermuda and Newfoundland whilst a warm-front wave is developing east of Newfoundland. Figure 6 shows the situation at 0001 GMT, 24 March. The warm-front wave has developed rapidly south-east of Greenland whence it moves eastwards towards northern Scotland on 25 March (Figure 7).

This change of type is a spectacular example of downward effects in the atmosphere; a change in the mid-stratosphere influences the subsequent tropospheric developments.

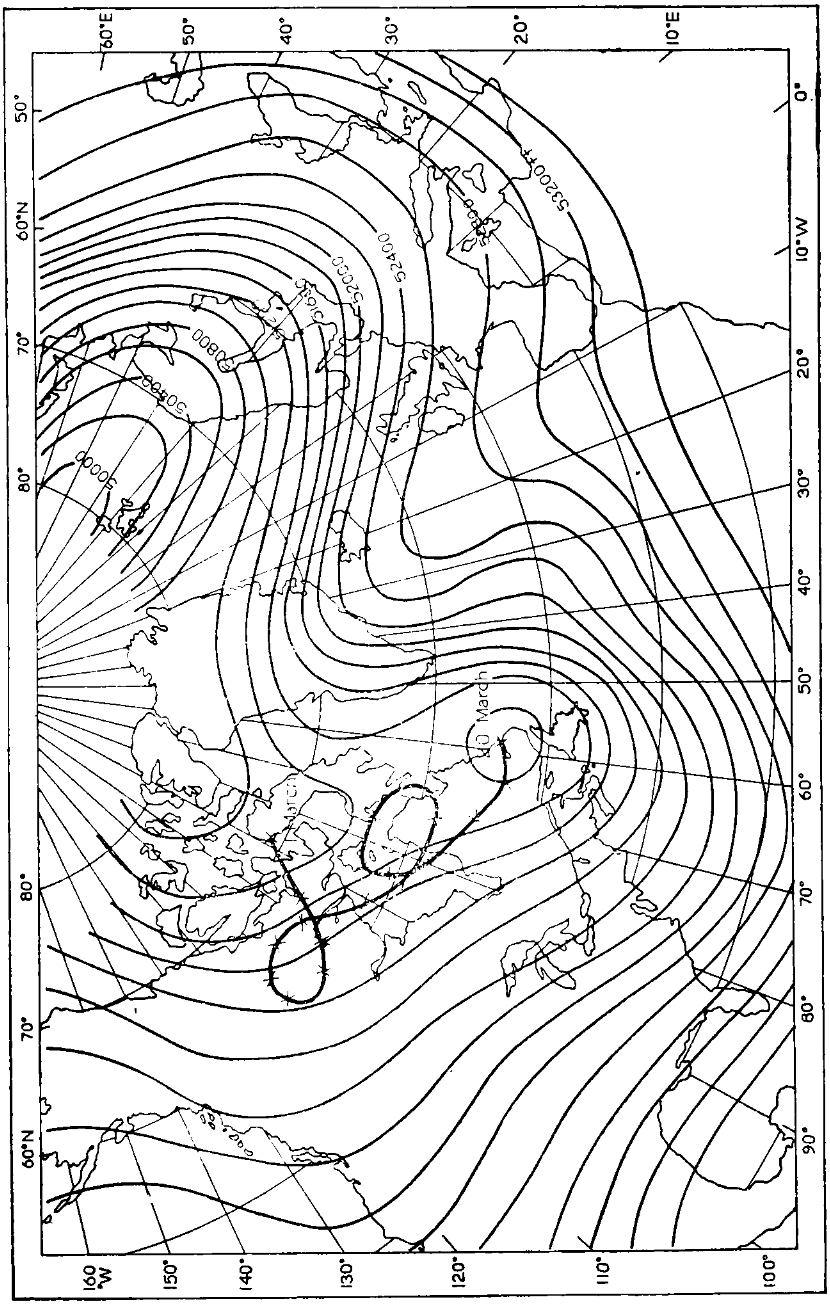

FIGURE I—100 MB CONTOURS FOR 0001 GMT, 20 MARCH 1962

x——x Track of closed circulation from 1–20 March

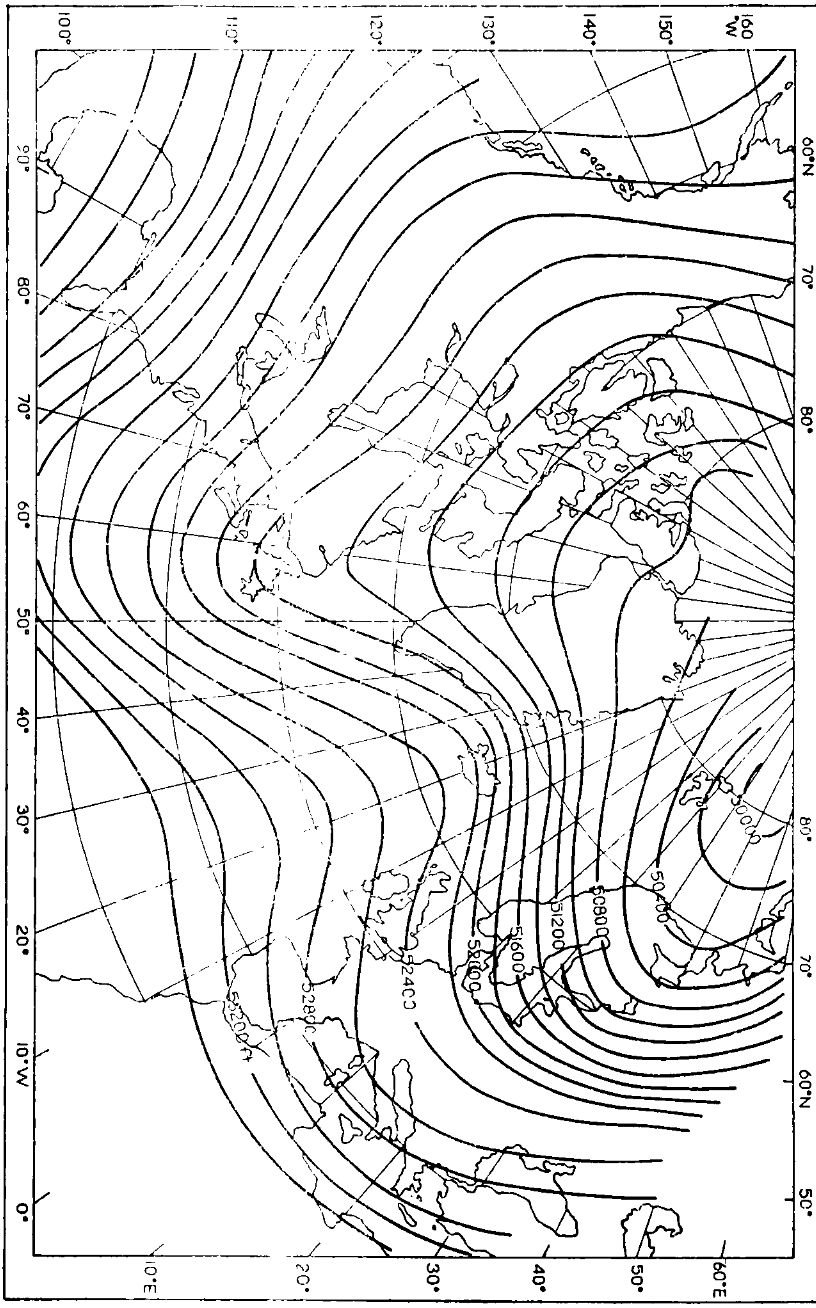

FIGURE 2—100 MB CONTOURS FOR 0001 GMT, 21 MARCH 1962

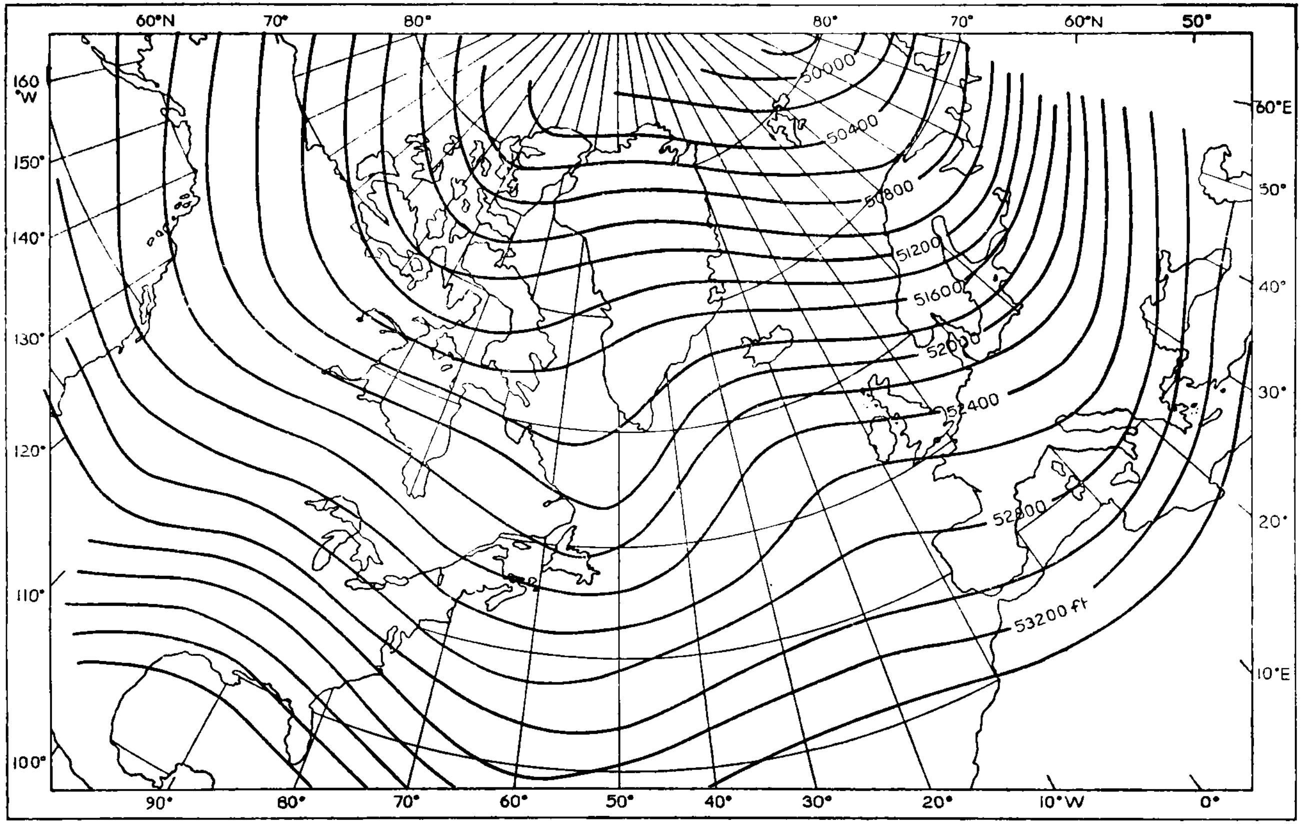

FIGURE 3—100 MB CONTOURS FOR 0001 GMT, 22 MARCH 1962

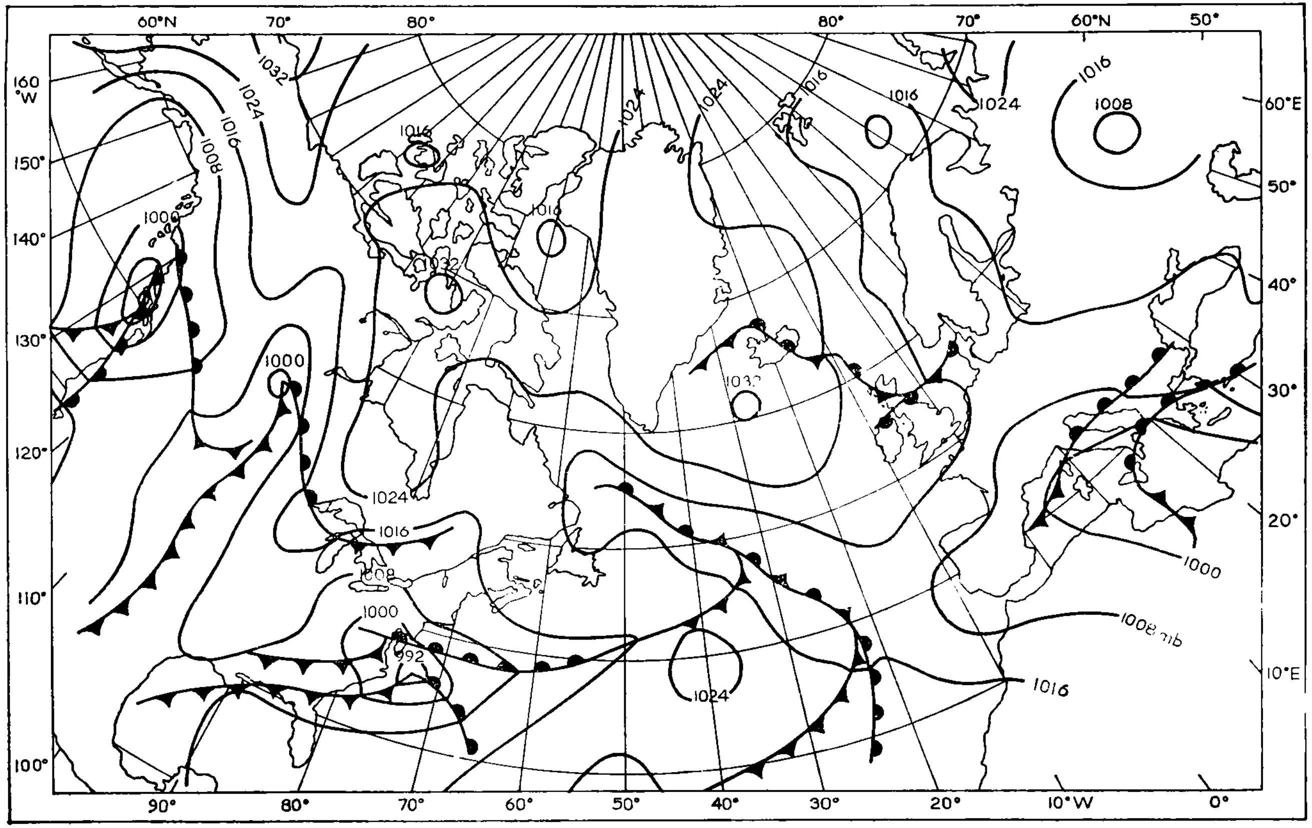

FIGURE 4—SURFACE CHART FOR 0001 GMT, 22 MARCH 1962

Isobars at 8 mb intervals

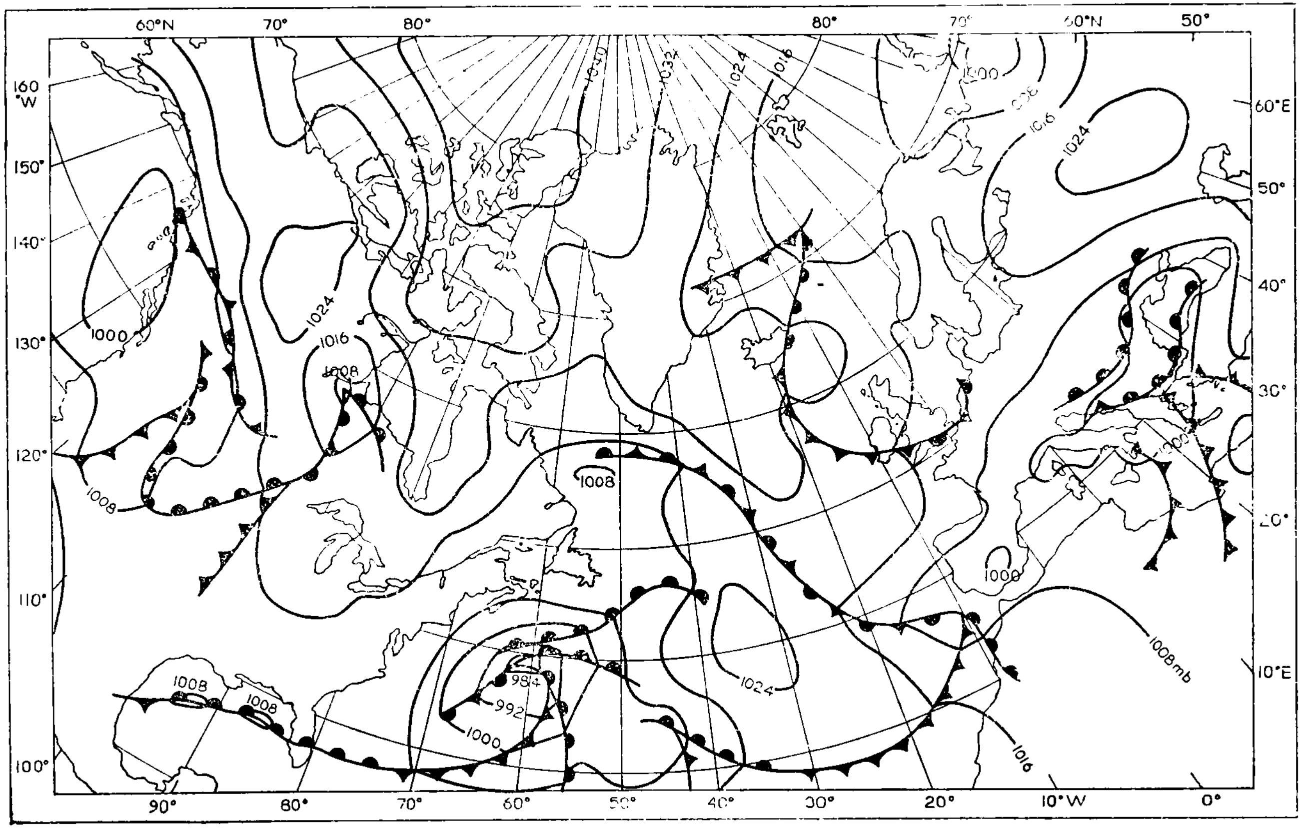

FIGURE 5—SURFACE CHART FOR 0001 GMT, 23 MARCH 1962
Isobars at 8 mb intervals

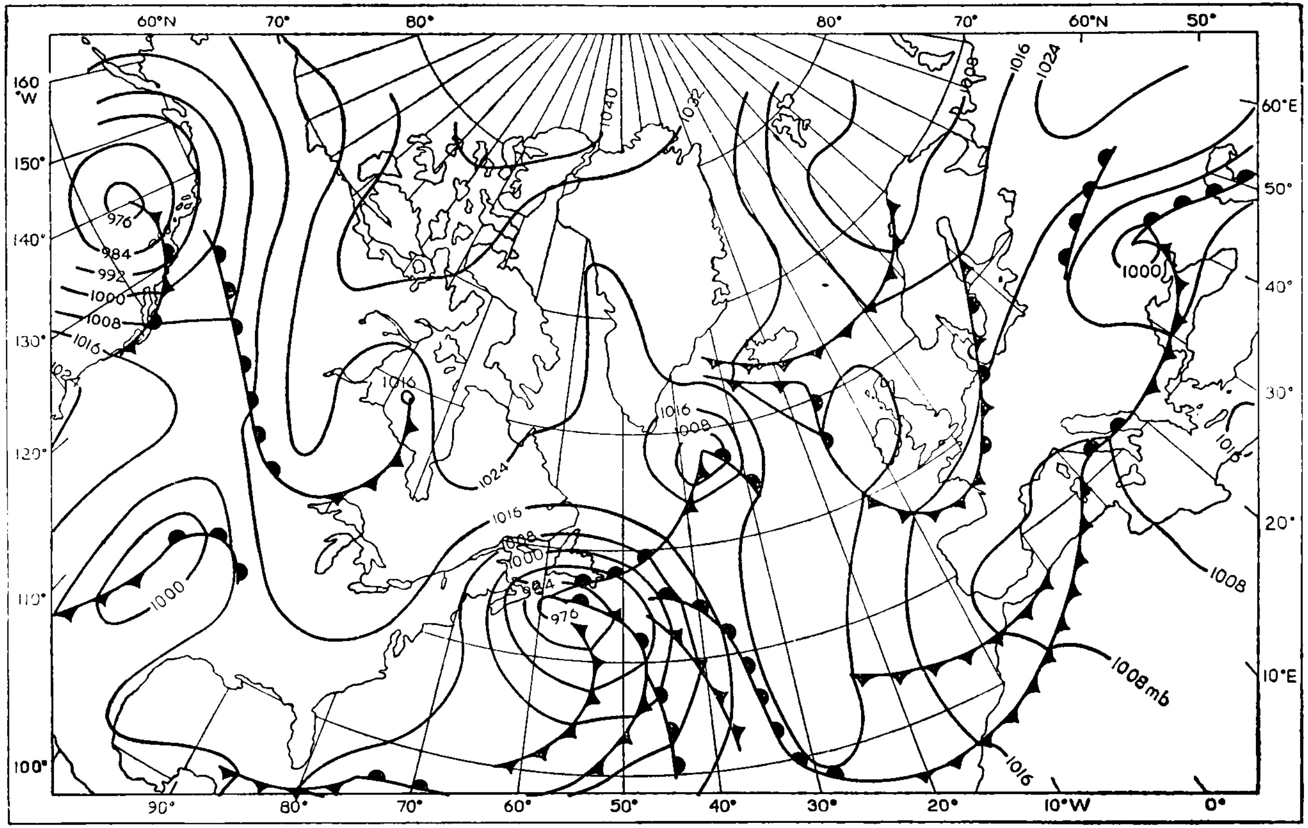

FIGURE 6—SURFACE CHART FOR 0001 GMT, 24 MARCH 1962

Isobars at 8 mb intervals

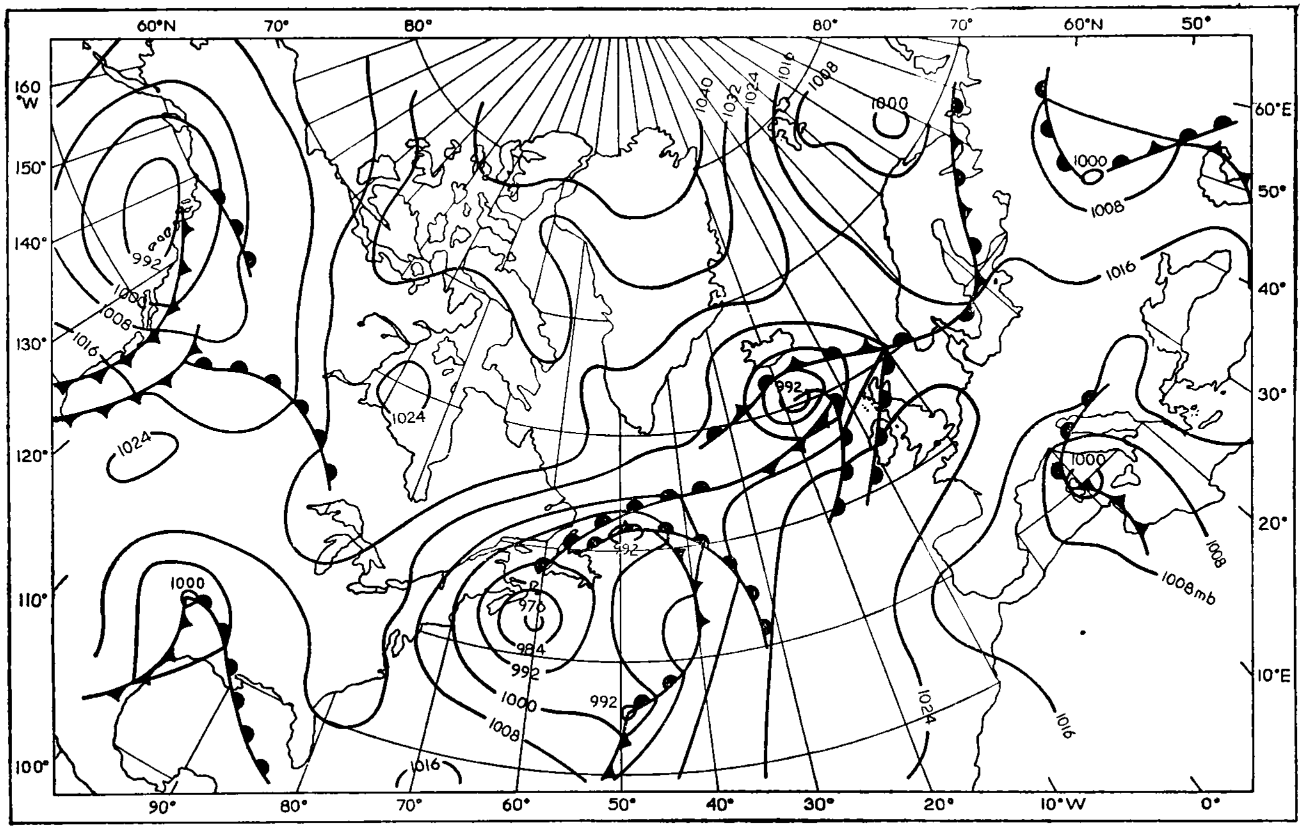

FIGURE 7—SURFACE CHART FOR 0001 GMT, 25 MARCH 1962

Isobars at 8 mb intervals

551.5:77

TIME-LAPSE PHOTOGRAPHY IN METEOROLOGY

By D. J. GEORGE

For many years the cine-camera has been used for scientific photography, one particular technique being the use of time-lapse photography to show movement or growth which occurs in nature on a time scale too slow to be noticeable to the human eye, for example growth of plants and cloud evolution. Cinematograph films are usually projected at a speed of 16 frames per second (silent films) or 24 frames per second (sound films) so if the subject is photographed at a slower rate, the projected picture will show a speed up of movement depending on the ratio of camera speed to projection speed.

Time-lapse photography has been used intermittently in meteorology since the beginning of the century. A survey by Farquharson[1] in 1939 mentions the use of the cine-camera by Sir Napier Shaw in 1911[2] to show cloud development ahead of a depression, and the use of the animated diagram technique to illustrate the evolution of a depression. Several workers used the time-lapse method for photographing clouds in the 1920's and 1930's, amongst others, Devaux,[1] Masanao Abe,[3] Idrac,[4] Kampé de Fériet[5] and Linke.[6] Professor Brunt[7] used the method in this country to show the motion of stratocumulus cloud, whilst Mügge[8] made a series of films in Germany, copies of which are in use in the Meteorological Office Training School.

Since the war, improved cameras and films have been available, and several workers have used time-lapse cameras for cloud investigations, in conjunction with still cameras, aircraft and a dense network of ground and upper air stations, (for example Schaefer,[9] Larsson,[10] Ludlam and Saunders,[11] Holmboe and Klieforth[12] and Conover[13]). A series of time-lapse films on clouds by Mügge and Wachter are available in the World Meteorological Organization (WMO) Film Loan Service.[14] Several enthusiastic glider pilots and photographers have made time-lapse sequences of clouds using quite modest equipment.

A 16 mm cine-camera has been in use at the Meteorological Office Training School since late 1960, in order to make instructional colour films on clouds. The camera (Bell and Howell 627) has an Angenieux wide-angle fixed-focus 10 mm lens, and is connected to a battery operated intervalometer which takes single frames at intervals which can be varied from 1 second to 15 seconds. The camera is mounted on a strong tripod fitted with a pan and tilt head, whilst exposure is adjusted manually after checking the lighting with an exposure meter (see Plate V). Some experimenting was necessary to find the appropriate time interval to use, as too large an interval resulted in a jerky motion of the subject, whilst too short an interval resulted in little visible change in the cloud. Intervals used have varied from 1 second to 10 seconds, depending on the angular velocity of the cloud. The graph (Figure 1) shows the relationship between angular velocity of the cloud and time-lapse interval used. One difficulty is that high clouds, for example glaciating cumulonimbus tops, are quickly obscured by lower clouds which have a greater angular velocity. Also, the horizontal speed of the cloud may be such that the cloud is lost in the distance before a sufficient length of film is obtained.

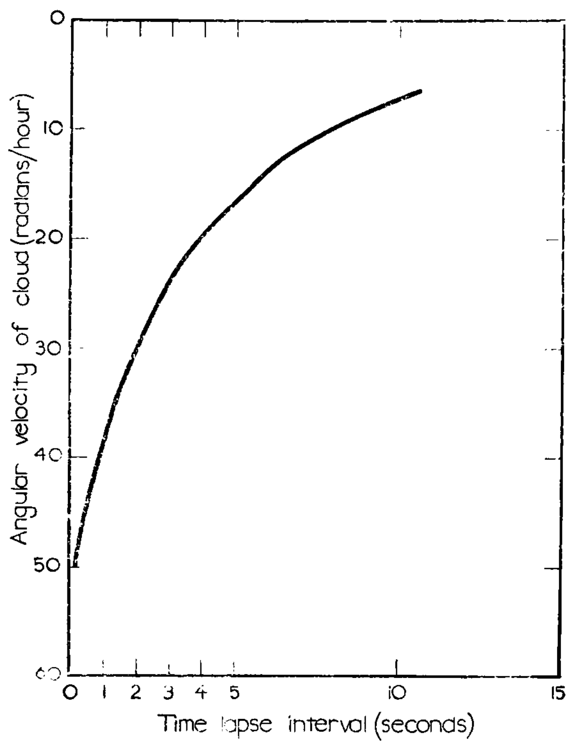

FIGURE I—RELATIONSHIP BETWEEN ANGULAR VELOCITY OF CLOUD AND TIME-LAPSE INTERVAL USED

Subjects photographed have included growth and diurnal variation of cumulus, formation of stratocumulus cumulogenitus, orographic cumulus, cumulonimbus, effect of frontal cloud cover on convection, altocumulus castellanus and floccus, glaciation of an altocumulus sheet, passage of fronts, jet-stream cirrus, wave clouds and dispersal of fog. A 30-minute film has been prepared on convection cloud[15] which includes the cloud scenes and relevant synoptic surface and upper air charts and diagrams, with written commentary. This film may be of interest to RAF flying schools and gliding clubs. A second film is to be prepared on layer cloud.

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METEOROLOGICAL OFFICE DISCUSSION

Some variations of temperature and wind in the lower stratosphere

The third Monday Discussion of the season was held at the Royal Society of Arts on 21 January 1963. The subject was 'Some variations of temperature and wind in the lower stratosphere'.

In opening the discussion Mr. R. A. Ebdon referred to the early ideas of the stratosphere as a region of comparative calm. However, since about 1950—due to improvements in the performance of the radiosonde, some very interesting variations have been observed in stratospheric winds and temperatures.

Dealing with high latitudes of the Northern Hemisphere he described the variations in wind and temperature which occur from winter to summer. He went on to describe the year-to-year variations which occur during the period of the 'final warming' and the break-down of the stratospheric circumpolar vortex in the late winter or early spring. It was pointed out that 'sudden' (or 'explosive') warmings and coolings of the stratosphere are also a common occurrence over the British Isles during late winter and early spring.

Attention was then focused on lower latitudes and the recently detected tropical stratospheric wind fluctuation. Using data for Canton Island (02°46′S, 171°43′W) and other equatorial stations it was shown that, during the last nine years or so, equatorial stratospheric zonal wind components have displayed a fluctuation with a periodicity varying between about 22 and 29 months. The fluctuation consists of a change from easterly to westerly winds or vice versa, and is seen first at high levels, taking about 6 months to descend from 25 mb to 60 mb. The amplitude of the fluctuation decreases with height between 25 mb and 80 mb. Near the equator the stratospheric winds show little or no annual variation and the dominant feature of the wind pattern is the fluctuation of approximately 26 months; whereas away from the equator in the tropics there is a very marked annual variation, although the fluctuation is still present. The amplitude decreases with distance from the equator and is only just detectable at latitudes 25–30 degrees. The 12-monthly running means of equatorial stratospheric temperatures also show the approximately 26-month fluctuation.

Mr. Ebdon concluded by saying that such data as are available provide evidence for suggesting that the fluctuation was in existence during the early years of this century.

The discussion, opened by the Director-General, covered a variety of topics ranging from the possible effect of stratospheric fluctuations on surface weather to the suggestion that the stratospheric wind fluctuation might extend to the ionosphere. Several speakers wondered why 'sudden warmings' did not occur at other times of the year in high latitudes and mention was made of a possible 2-year periodicity in the strength and behaviour of the stratospheric circumpolar vortex. Regarding low latitudes, the need for a mechanism to produce westerly winds at the equator was discussed.

METEOROLOGICAL OFFICE NEWS

Seafarers' Education Service 1961 competitions

We have heard with pleasure of the success of two members of the meteorological staff in the ocean weather service in the competitions run by the Seafarers' Education Service.

In the 1961 competitions Mr. P. W. Hewitt, Scientific Assistant aboard O.W.S. *Weather Reporter* gained first prize in the photographic competition. Mr. Hewitt's subject was 'Boat Drill' described by the judges as a "picture which combines dramatic interest with good photography, each face providing an interesting study and the whole conveying an authentic sense of the occasion". The picture was reproduced as the cover of the summer 1962 issue of *The Seafarer*, the Quarterly Journal of the Seafarers' Education Service. The photograph actually illustrates an air–sea rescue exercise at sea. One 'survivor' is lying on a stretcher covered with a blanket, others are sitting in the boat with blankets wrapped round them, while the one in the foreground is being hove on board with a canvas belt and line. (Note the man with the 'walkie-talkie' radio set near the officer in the stern of the boat.) See Plate I.

In the 1962 competitions Mr. J. Connolly, Experimental Officer aboard O.W.S. *Weather Monitor* gained second prize in the painting competition. Mr. Connolly submitted three paintings, all of Irish landscapes, described by the Director of the Service as "very pleasant and competent work". One of these paintings will have a place in the Services Exhibition which is annually circulated to various seamen's clubs and nautical colleges.

Successes have also been gained by men in other branches of the ocean weather service. In 1959 Mr. C. E. Birtchnell, Radio Officer aboard O.W.S. *Weather Monitor*, shared the third prize in the essay competition whilst Mr. J. Stuart-Welldon, Assistant Steward in O.W.S. *Weather Watcher* was commended for his poetry entry. In 1961 the same Mr. Birtchnell, who had then moved to the *Weather Reporter*, was highly commended for a painting which was subsequently displayed in an exhibition.

These annual competitions form an integral part of the work of the Seafarers' Education Service. Competitions are held for short stories, photographs, essays, articles, poems, models, paintings, handicraft and crosswords, with prizes ranging from £20 to 15s. They are open to all British seafarers, irrespective of branch, rank or rating, and also to the lighthouse service. As an example of the range of these competitions, this year the essays may be on (*a*) Ships and the Future, (*b*) Freedom from Hunger, (*c*) Christmas at Sea, (*d*) Character Study and (*e*) My Favourite Book. The painting competition may be of any subject; the handicraft, anything done by hand; the short story competition, a short story on any theme, whilst the poetry competition is for a poem not exceeding 25 lines on any subject. The photographic competition is open for original photographs of ships and other nautical subjects of general rather than of personal interest.

In addition, the service will consider articles and crosswords for publication in their Quarterly Journal with payment. Mr. C. E. Birtchnell, mentioned above as a prize winner, also received payment for an article in 1960.

The Far East Air Force Command Sailing Championships

The Far East Air Force Command Sailing Championships were held in December 1962 at RAF Seletar Yacht Club, and the winning team was captained by Mr. P. F. McAllen, Senior Meteorological Officer 224 Group. Mr. McAllen, was posted to 224 Group shortly before the championships and was given special permission to sail for RAF Changi Yacht Club where he has held the post of Captain of Boats for the past two years. The other teams which entered the championships were from RAF Yacht Clubs at Hong Kong, Gan, Seletar and Tengah, and the team-racing was in International Snipes. The weather was good with showers bringing a gusty but welcome relief from the light northerly winds.

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THE METEOROLOGICAL MAGAZINE

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THE INTERNATIONAL METEOROLOGICAL ORGANIZATION AWARD TO DR. R. C. SUTCLIFFE, C.B., O.B.E., F.R.S.

By the DIRECTOR-GENERAL

At its Fifteenth Session in Geneva this year, the Executive Committee of the World Meteorological Organization (WMO) awarded the International Meteorological Organization (IMO) Prize for 1963 to Dr. R. C. Sutcliffe, C.B., O.B.E., F.R.S., Director of Research in the Meteorological Office. Dr. Sutcliffe thus becomes the second British subject to receive this award, the first being Mr. E. Gold, C.B., O.B.E., F.R.S., in 1958.

The IMO Prize was created by the Second Congress of WMO in 1955. The Prize consists of a gold medal, a substantial sum of money and a certificate giving the citation of the award, bearing the signature of the President of WMO and the official seal of the Organization. The award is made annually by the Executive Committee by selection from names proposed by Member countries and it is laid down that "in the selection of the recipient, both scientific eminence and the record of work done in the field of international meteorological organizations should be taken into consideration". The inscription on the medal "Societas Gentium Meteorologica. Pro singulari erga scientiam meteorologicam merito" expresses this thought most concisely.

Dr. Sutcliffe is so well known that it is hardly necessary to go into the details of his long and distinguished career in meteorology. He entered the Meteorological Office in 1927 and his official record covers service both at home and overseas. His best known scientific work is the creation of the development theory of synoptic-scale disturbances, in which the importance of the vertical component of vorticity was brought out for the first time in a clear quantitative fashion. This research helped to lay the foundations of present-day 'numerical forecasting', much of which, to quote one pioneer in this field, is "in the spirit of Sutcliffe's work".

Dr. Sutcliffe became the first Director of Research in the Meteorological Office in 1957, following the Brabazon reorganization. He was elected a Fellow of the Royal Society in the same year. From 1957 to 1961 he was President of the WMO Commission for Aerology and he has also acted as Secretary of the International Association of Meteorology and Atmospheric Physics.

This award has given great pleasure to Dr. Sutcliffe's many friends, both within and without the Office, and is very real evidence of the high regard that his scientific work and his pleasant personality have won all over the world.

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A SIMPLE INSTABILITY INDEX FOR USE AS A SYNOPTIC PARAMETER

By C. J. BOYDEN

Introduction.—An instability index is a concise measure of the state of a column of the atmosphere in respect of its temperature structure and sometimes its humidity. Its purpose is to indicate the likelihood of the air becoming unstable when it is subjected to such processes as surface heating and horizontal convergence. The index is not usually related to the weather until energy is supplied in a specified way. Thus air with a high instability index may not produce weather of an unstable character over the sea but thunderstorms are likely to develop in it when it arrives over a heated land surface.

The index of vertical stability most widely known is probably that due to Showalter.[1] Essentially his index is a measure of how near the atmosphere is to releasing potential instability between the levels of 850 mb and 500 mb. Galway[2] introduced a similar index for which a forecast is made of the temperature in the lowest layers. The Showalter index is related basically to the likelihood of instability resulting from convergence whereas the Galway index assesses the consequences of low-level heating, yet both are intended for use in forecasting thunderstorms. It may be that both processes are usually active in thunderstorms or simply that the conditions for potential instability are correlated with those which produce convection.

The index proposed by Rackliff[3] is little different from that of Showalter. The differences are that 900 mb, rather than 850 mb, is the level from which air is assumed to be lifted and the 900 mb wet-bulb potential temperature is used in place of the wet-bulb temperature obtained by lifting the air to the 500 mb level. The limitations of using a potential temperature in this index have been pointed out by Jefferson.[4]

Most indices are designed for use in relation to thunderstorms and similar violent phenomena. They are usually computed from upper air ascents made at night and it is assumed, with fair justification in the circumstances, that the only change in the local atmosphere in the next 12 or 18 hours will arise from surface heating. This is broadly true since heat thunderstorms commonly occur where there is little advection, at least in the lower layers. Nevertheless, about half the summer thunderstorms over the British Isles occur in the vicinity of a front, though often a weak one, and this points to a need for a method of assessing the probability of thunderstorms when the local upper air changes with time are not negligible. It is believed that an instability index is rarely, if ever, used as a synoptic parameter in the sense that instability isopleths are regularly drawn over a complete upper air chart and followed from day to day as are depressions and anticyclones. The nature of the components of an instability index suggests there would be no great difficulty in doing this, but it would take time. The present paper introduces an index which appears to meet all major requirements and can be plotted on a 700 mb chart for all stations over the North Atlantic and Europe within five minutes.

The main requirements in an instability index for synoptic use are the following:

(i) The index must be obtainable quickly.

(ii) The range of values of the index must be large enough for the isopleth pattern to show salient features.

(iii) The index should not be determined to more than a small extent by surface temperature for, if it were, the pattern of isopleths would be seriously influenced by the distribution of land and sea.

(iv) It must be possible to forecast the future pattern from present and past patterns of instability index; since the change is likely to be dominated by advection it is desirable that the layer from which the index is evaluated should not be deep, for then the index would change by shear along the direction of the wind used in estimating the advection.

(v) The index must have a well-defined relationship to the weather in specified circumstances.

The proposed instability index.—In devising an instability index to meet these requirements, the aim was to forecast thunderstorms and heavy rain over south-east England in the months of May to September, this being the period when thunderstorms over England are most frequent. Results were based on the three summers from 1960 to 1962. Reports of thunderstorms and heavy rain or heavy showers were taken from the Beaufort letters describing the weather between 0900 and 2100 GMT each day, the observing stations used being Kew, London (Heathrow) Airport, Gatwick, Thorney Island, Hurn, Felixstowe, Gorleston, Mildenhall and Cardington. This choice of stations was made because they comprise nine of the first ten in the *Daily Weather Report** and give a reasonable network over south-east England. Surface reports were supplemented by sferic (atmospheric) observations over the same hours of the day. The instability index was computed from the Crawley upper air report.

Initially the assumption was made, and appears to be justified, that the development of heavy showers and thunderstorms over land on a summer afternoon depends largely on the mean lapse rate up to 700 mb only, though on most occasions this is related to the lapse rate above that level. If this layer is in a state of neutral static stability for saturated air (that is, with dry-bulb temperatures along a saturation adiabatic) and has a 700 mb temperature of —20°C, the 1000–700 mb thickness is 275 decametres. For a 700 mb temperature of 0°C the thickness is 294 decametres and for +20°C, 313 decametres. (This range of temperature easily covers the extremes ever reached over Crawley in the summer months.) If these temperatures are subtracted from the corresponding thicknesses the resulting figures are 295, 294 and 293, respectively. They are nearly equal because the thickness of the layer in decametres happens to be numerically not very different from its mean temperature in degrees absolute.

In devising the instability index it was assumed that the 1000–700 mb thickness minus the 700 mb temperature (°C) was constant ($\simeq$294) for neutral stability. Instability was then measured by the extent to which this difference exceeded the constant, and stability by the reverse. In other words, air was

*Meteorologicl Office. *Daily Weather Report, London.*

classed as unstable if the 700 mb temperature was low for the thickness and vice versa. The precise formula adopted for the instability index (I) was

$$I = Z - T - 200,$$

where Z = 1000–700 mb thickness in decametres,
T = 700 mb temperature in °C,

and 200 is subtracted to remove unwanted figures.

It will be noted that I is strictly a measure of the mean stability in the layer below 700 mb. It cannot be used as a measure of the instability in, say, the lowest kilometre or two, where there might be cold and unstable air beneath an inversion; such an atmosphere would have a stable index. This limitation is not of importance since we are not concerned with precipitation forming at low levels, and the index is not intended for assessing the probability of slight or even moderate showers. A similar situation arises when the index is calculated from an ascent made through a frontal surface which is below the 700 mb level. This index is again low and is not representative of the air which is producing most of the frontal rain. Nevertheless, this situation does not occur frequently and the indices affected are easily recognized on a chart.

Local changes of the instability index.—The next consideration is how clear a synoptic pattern the instability index is likely to provide and how successfully the changes in the pattern can be forecast. At Crawley, in the months May to September, the index was found to lie between 88 and 100, about 85 per cent of the values being within the range 91 to 96. These extremes seem to apply quite well over the whole area from Greenland to the Mediterranean, though indices exceeding 100 occurred not infrequently over southern Europe. No difficulty was found in drawing smooth isopleths of instability index when allowance was made for a possible error of unity in any observation. Over the Atlantic a reliable analysis was found to require the drawing of a sequence of charts, as was to be expected.

Analysis of the Crawley indices in the summer of 1962 showed the changes of I between midnight and the following midday to range from —9 to +5, though 60 per cent of them lay between —1 and +1. The root mean square change was 2.07. Thus the assumption that the midnight index could be used to forecast the likelihood of afternoon thunderstorms (in both frontal and non-frontal situations) would have been acceptable more than half the time but seriously misleading on occasions. Since the instability index is derived from that part of the atmosphere below 700 mb, a forecast of the midday value was made from the midnight chart on the assumption that the index isopleths moved with the 700 mb wind shown on that chart. For the 153 days this method gave no error exceeding 3 and 72 per cent of the errors lay between —1 and +1, their root mean square being 1.35. Since I is a whole number which is the difference between two quantities each rounded to the nearest whole number this result is regarded as justification for the advection of the index in this way over 12 hours. Over longer periods a factor such as subsidence would introduce non-advective changes, but there is reason to think that most of the errors would be remote from areas where I was critical in relation to thunderstorms.

In forecasting the index 12 hours ahead one would have expected to find a small but not negligible diurnal variation. If the temperature structure of the air below 900 mb were to change from an isothermal lapse rate at midnight to a dry adiabatic at midday, there being no change above 900 mb, then the instability index would increase by about 1.5 with no change after convection reached the 700 mb level. An increase of, say, 0.5 might seem a reasonable average for all days in the summer months. It was surprising, therefore, to find that on the average there was a decrease of 0.25 decametres in the 1000–700 mb thickness at Crawley, a decrease of 0.17°C in the 700 mb temperature and a drop of 0.1 in the instability index. When the analysis was confined to non-frontal nights and days the thickness change was +0.4 decametres and *I* increased by nearly 0.2. These figures suggest that the radiosonde readings are over-compensated for radiation, so a similar computation was made for Trappes, near Paris, including both frontal and non-frontal days. Here the thickness change was +0.12 decametres (against —0.25 at Crawley) and the 700 mb temperature change +0.25°C (against —0.17). Like Crawley, Trappes showed a decrease in *I* from midnight to midday of 0.1. Whether the diurnal variation of *I* is as low as this in other countries has not been ascertained, but the instability charts that have been drawn suggest it is small throughout most of Europe.

The instability index in relation to weather.—The next point to be considered is the significance of the instability index in terms of weather. For this purpose the 459 days of May to September, 1960–62, were each classed as non-frontal (*N*) or frontal (*F*), according to whether the charts in the *Daily Weather Report* showed south-east England to be in any way affected by a front between 0900 and 2100 GMT. Many of the fronts were, of course, weak, so the *F* days included a number of situations that were physically as appropriate to the *N* class. The items tabulated (for the night period as well) were the Crawley 1000–700 mb thickness and 700 mb temperature, the number of stations reporting heavy showers or heavy rain, the number of stations reporting thunderstorms (including, without distinction, lightning seen and thunder heard), the total rainfall from the nine stations and the days with sferics over the area within the 12-hour period.

In the three summers there were altogether 91 days (0900–2100 GMT) on which a thunderstorm was reported by at least one of the nine stations. On all but eight occasions these were confirmed by sferic reports at some time on the same day, the exceptions presumably being due to the occurrence of thunderstorms between the times of sferic observation. In addition there were 43 days when sferics were observed but thunderstorms were not reported from the ground, having evaded the surface observational network. From these figures there seems no doubt that the total number of days with thunderstorms was at least 150, an average of one day in three. The frequency of days of heavy precipitation was much the same as of thunderstorms, though slightly greater when there were fronts and slightly less at other times.

Figure 1 shows, for non-frontal days, the distribution of the instability index and the frequency of days on which thunderstorms or heavy rain occurred somewhere over the area. Figure 2 is a similar histogram for frontal days. The distribution of high-index days is much the same in the two diagrams but the lower indices of 91 and 92 are more frequent on *N* days, as is to be expected since anticyclonic weather came in this class. On both diagrams there is a marked increase in thunderstorms when *I* reaches 94 and a maximum in the proportion of thunderstorm days at $I = 95$ or more. It will be remem-

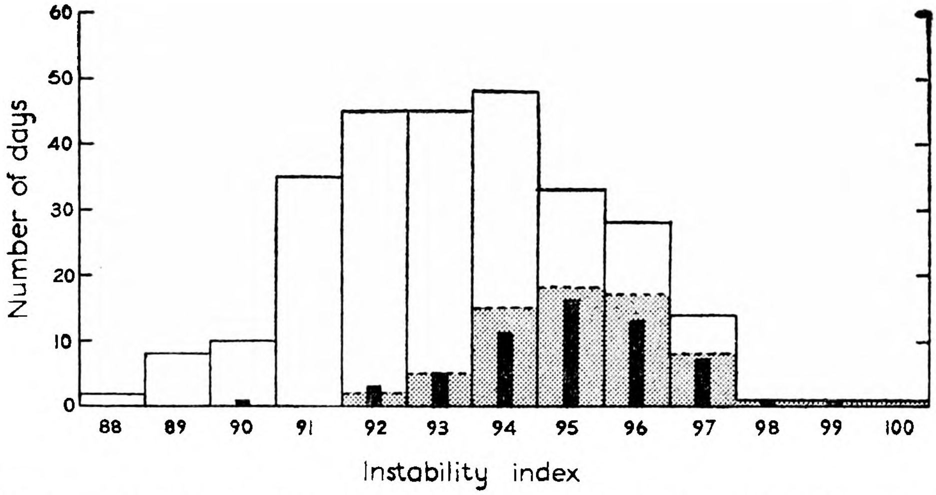

FIGURE 1—FREQUENCY OF NON-FRONTAL DAYS (MAY–SEPTEMBER 1960–62) FOR EACH VALUE OF THE INSTABILITY INDEX

Number of days of thunderstorms —— light shading
Number of days of heavy showers ——— heavy shading

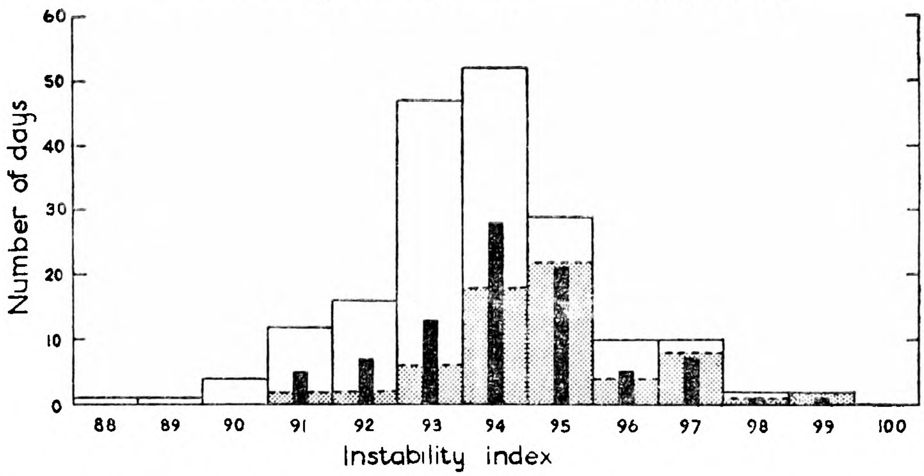

FIGURE 2—FREQUENCY OF FRONTAL DAYS (MAY–SEPTEMBER 1960–62) FOR EACH VALUE OF THE INSTABILITY INDEX

Number of days of thunderstorms —— light shading
Number of days of heavy showers —— heavy shading

bered that $I = 94$ corresponds to mean neutral stability below 700 mb, but the sharpness of the separation is surprising since I involves a computational error which can be as high as unity and, moreover, any variations of I during the 12-hour period were disregarded. The change between indices 93 and 94 is confirmed by Figure 3, which shows, for non-frontal days, the frequencies of various categories of average rainfall from the nine stations. These averages have little absolute significance since on many occasions most of the rain may have fallen at only one or two stations (so Figure 3 should not be regarded as a probability diagram for a particular place). However, the increase in average rainfall exceeding 1.0 mm when I reached 94 is unmistakable. It will also be noted that with an index of 93 or less on a non-frontal day there is an 80 per cent probability that no measurable rain will occur at any of the nine stations. A similar analysis was not made of frontal days because any discontinuity would have been masked by the contributions from slight and moderate rain.

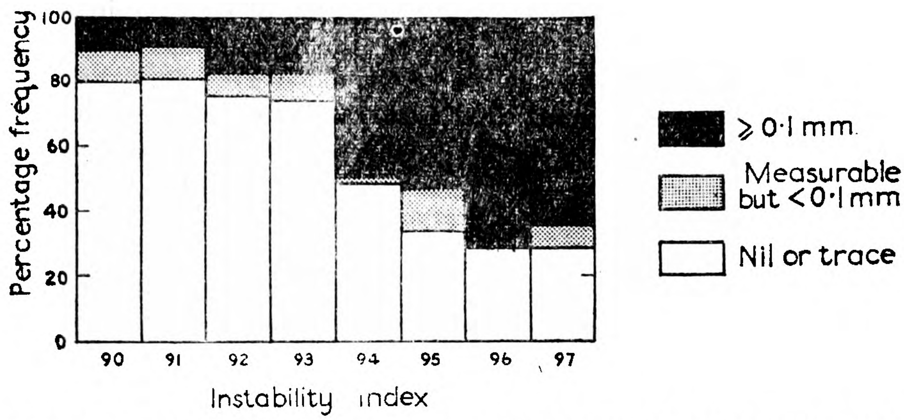

FIGURE 3—VARIATION WITH INSTABILITY INDEX OF THE FREQUENCY OF DIFFERENT AVERAGE RAINFALL TOTALS FOR THE PERIOD 0900–2100 GMT ON NON-FRONTAL DAYS

Table I, in which frontal and non-frontal days are treated separately, includes the information available in Figures 1 and 2 and gives various probabilities according to whether the index is 94 and above or 93 and below.

TABLE I—RELATIONSHIPS BETWEEN THE INSTABILITY INDEX AND THE WEATHER OVER THE AREA*

(*a*) Non-frontal days (0900-2100 GMT)

Instability index at 1200 GMT	88	89	90	91	92	93	94	95	96	97	98	99	100	Total
No. of days	2	8	10	35	45	45	48	33	28	14	1	1	1	271
No. of days with a thunderstorm in the area	—	—	—	—	2	5	15	19	17	9	1	1	—	69
No. of days with a heavy shower in the area	—	—	1	—	3	5	11	16	13	7	1	1	—	58

	Days with instability index ≤ 93 *per cent*	Days with instability index ≥ 94 *per cent*	All days *per cent*
Probability of a day with a thunderstorm in the area	10	49 (60 when $I \geqq 95$)	25
Probability of a thunderstorm at a chosen station	1	14	7
Probability of a heavy shower in the area	6	39	21
Probability of a heavy shower at a chosen station	1	10	5

(*b*) Frontal days (0900-2100 GMT)

Instability index at 1200 GMT	88	89	90	91	92	93	94	95	96	97	98	99	100	Total
No. of days	1	1	4	12	18	47	52	29	10	10	2	2	—	188
No. of days with a thunderstorm in the area	—	—	—	2	2	6	18	22	4	8	1	2	—	65
No. of days with heavy rain or a heavy shower in the area	—	—	—	5	7	13	28	21	5	7	1	1	—	88

	Days with instability index ≤ 93 *per cent*	Days with instability index ≥ 94 *per cent*	All days *per cent*
Probability of a day with a thunderstorm in the area	12	52 (70 when $I \gtrsim 95$)	35
Probability of a thunderstorm at a chosen station	2	9	6
Probability of heavy rain or a heavy shower in the area	30	60	47
Probability of heavy rain or a heavy shower at a chosen station	9	15	12

*The area includes the nine stations: Kew, London (Heathrow) Airport, Gatwick, Thorney Island, Hurn, Felixstowe, Gorleston, Mildenhall and Cardington.

The contrasts are quite striking except in the case of heavy rain in frontal situations. It will be noted that if heavy rain or thunderstorms occur in south-east England at any time in the period 0900–2100 GMT the odds are four or six to one against a particular observer being aware of it from his personal observation. This is relevant to the wording of a local forecast as distinct from an area forecast. In forecasting for, say, a small town, it seems unwise to forecast a thunderstorm unless an instability index of at least 94 is expected.

It is fortunate that the relationship of thunderstorm probability to high or low index, as given in Table I, is practically the same for both classes. Thus if an instability index chart is used to locate areas where thunderstorms are likely to develop it is unnecessary to take account of the frontal situation. The explanation of this is partly that many summer fronts are weak and partly, one presumes, that frontal convergence is roughly equivalent to surface heating as a mechanism for inducing vertical instability.

Humidity in relation to instability.—In devising an instability index it is usual to make allowance for the humidity of the air. In the Showalter index, for example, a variation of one degree in the dew-point at 850 mb is about half as significant as the same variation in the temperature at 500 mb. It was therefore decided to tabulate dew-point and dew-point depression at 700 mb and 850 mb in relation to the index of the present paper, there being a possibility that this would differentiate between non-frontal high-index conditions (94–97) which gave thunderstorms or heavy rain and those which did not. In the rather shallow layer between these two levels the lapse rate of dew-point was found to be almost the same in thundery and non-thundery situations and so, too, was the mean difference in dew-point depression between the two levels. Thus if the vertical humidity structure, taken independently of the instability index, is important in relation to thunderstorms a deeper layer must be studied.

On non-frontal days the mean dew-point depression, both at 850 mb and 700 mb, was 4°C lower when thunderstorms developed with a high index than when they did not. On the other hand, the spread of the values was too great for the dew-point depression to have much forecasting use. It was noted, however, that a thunderstorm occurred only once with a dew-point depression at 850 mb greater than 8°C, a figure which was exceeded on 18 per cent of the high-index non-frontal days. Dryness of the air at low levels may explain the absence of thunderstorms in high-index conditions over parts of Europe, as for example over Spain as shown in Figure 12.

There may be several reasons why humidity, as a predictor additional to the instability index, is so loosely related to the development of thunderstorms. The most likely one seems to be that because of horizontal variations the humidity measured on a single ascent is insufficiently representative of the range of values occurring over the area in a 12-hour period.

The instability index chart.—The full use of a synoptic parameter, as well as its limitations, can be discovered only from experience in applying it; as yet there has not been time to use the instability index on more than a selection of days.

It has been found satisfactory to draw isopleths at intervals of two units and in doing so to allow a tolerance of unity in any observation. The pattern is usually featureless in some areas, but this is not of practical importance since in such areas the instability index is often uniformly high or low rather than near the critical level of neutral stability. The method of drawing an instability index chart is akin to that of drawing a thickness chart, in that the same use is made of continuity and of the advection of isopleths. For speed and convenience the instability index isopleths can be drawn on the 700 mb chart, the closed centres being marked 'S' (stable) and 'U' (unstable) to avoid confusion with the isobaric highs and lows.

In forecasting thunderstorms and heavy rain the forecaster makes much use of sferic observations. Their limitations are the diurnal variation of thunderstorms over land and the paucity of thunderstorms over the sea. On the other hand, charts of instability index are not materially affected by diurnal variations and do not depend on thunderstorm observations. They are particularly useful over the sea where continuity in the pattern from day to day enables the forecaster to make full use of the sequence of observations from ocean weather ships. Experience is nevertheless required in assessing non-advective changes of index. For example, on general grounds, one would expect cold air moving southwards over the Atlantic to have an increasing index which ultimately reaches a peak of about 95; during the earlier period the instability isopleths would therefore travel at less than the wind speed. Whether this is so can be found only by synoptic experience. Another guide which is subject to verification relates to the central part of a depression. Not only is this a region of fairly high index but the unstable area appears to extend or diminish only by deepening or filling of the depression. Changes due to the temperature of the underlying surface would be expected only if the path were markedly meridional.

Much remains to be learnt about the distribution of thunderstorms in relation to the pattern of the instability index. Sferics were rarely found with an index less than 94 but on the other hand a high index may occur over large parts of Europe without accompanying sferic reports. This was found on a number of occasions over Scandinavia and there it seemed reasonable to regard the cause as inadequate heating in high latitudes. When the expected sferics were missing from areas of southern Europe it seemed that this might be due in part to a limitation of the observing procedure, namely the 'swamping' of distant signals by thunderstorms nearer the observing stations. This is unlikely to be the complete explanation, so a high instability index should be regarded as a necessary condition for thunderstorms but one that needs to be supplemented by information from higher levels in certain situations.

Another aspect that was investigated was whether the 700 mb temperature had any bearing on the probability of thunderstorms over south-east England in non-frontal situations when the index was 94 or higher. With a 700 mb temperature at least 4°C below the monthly mean (this being —5°C in May, —2°C in June, 0°C in July and August and —1°C in September) introduced as an additional condition for thunderstorms the probability rose from 49 to 67 per cent, though to the exclusion of one-third of the thunderstorms that occurred. No such relationship was found on frontal days.

Examples.—Figures 4 to 12 give examples of the application of instability index charts in forecasting thunderstorms between May and September.

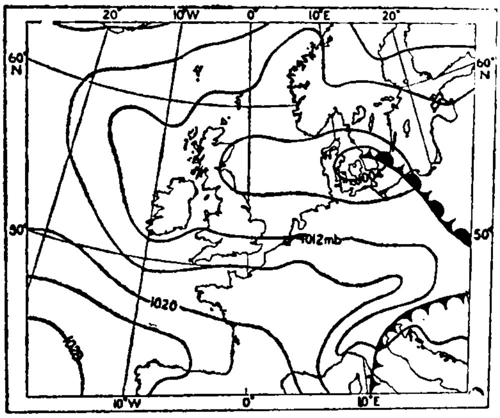

FIGURE 4(*a*)—SURFACE CHART FOR 1200 GMT, 10 MAY 1962

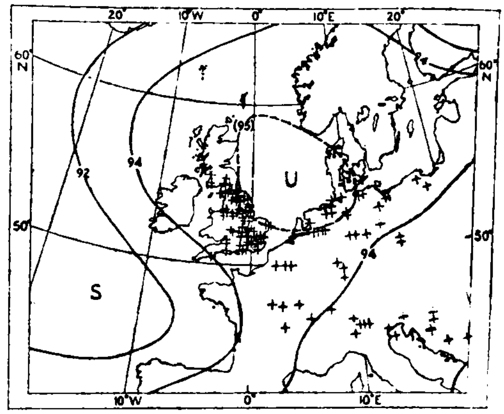

FIGURE 4(*b*)—INSTABILITY INDEX ANALYSIS FOR 1200 GMT, 10 MAY 1962
+ location of sferic reports, 1200–1700 GMT
S 'stable' U 'unstable'

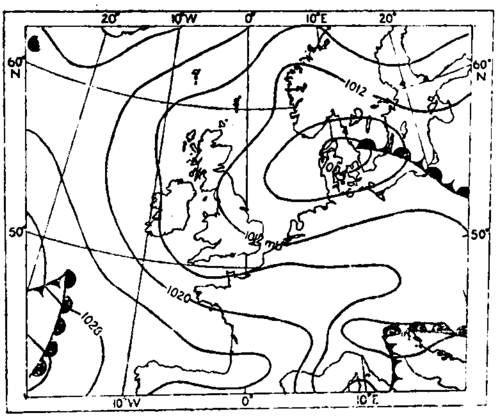

FIGURE 5(*a*)—SURFACE CHART FOR 0001 GMT, 11 MAY 1962

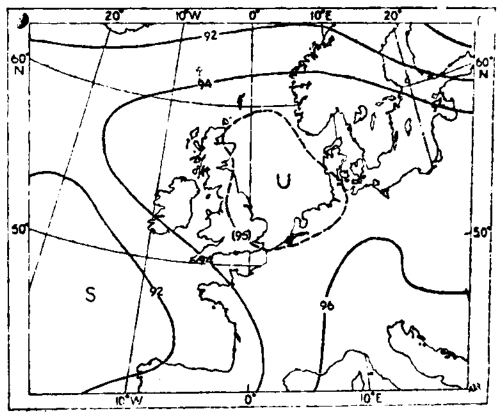

FIGURE 5(*b*)—INSTABILITY INDEX ANALYSIS FOR 0001 GMT, 11 MAY 1962
S 'stable' U 'unstable'

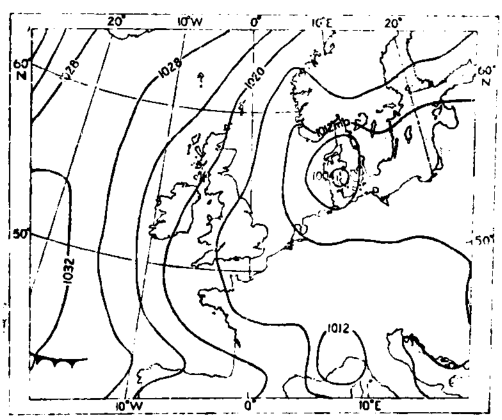

FIGURE 6(*a*)—SURFACE CHART FOR 1200 GMT, 11 MAY 1962

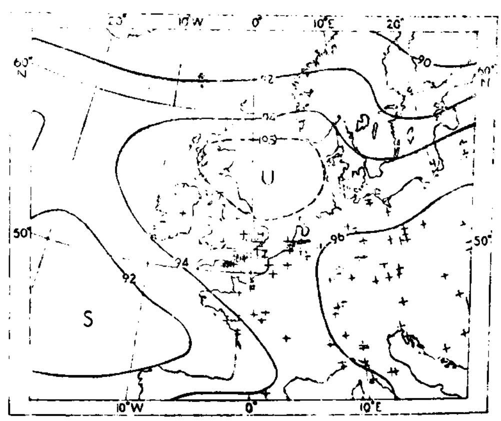

FIGURE 6(*b*)—INSTABILITY INDEX ANALYSIS FOR 1200 GMT, 11 MAY 1962
+ location of sferic reports, 1200–1700 GMT
S 'stable' U 'unstable'

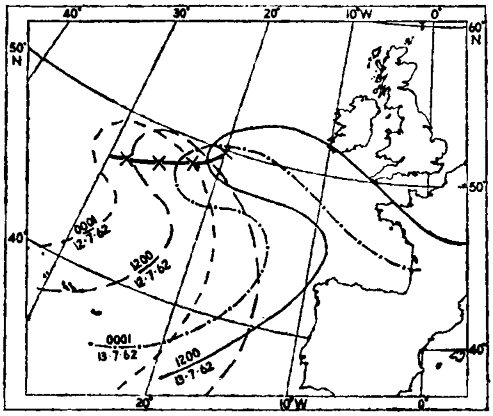

FIGURE 7—SUCCESSIVE POSITIONS OF 94 ISOPLETH OF INSTABILITY INDEX BETWEEN 0001 GMT, 12 JULY AND 1200 GMT, 13 JULY 1962
x–x movement of 700 mb low

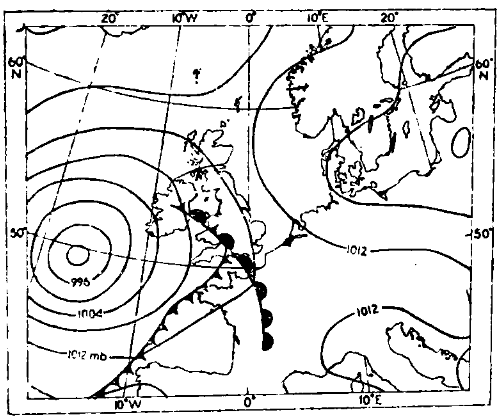

FIGURE 8(*a*)—SURFACE CHART FOR 0001 GMT, 14 JULY 1962

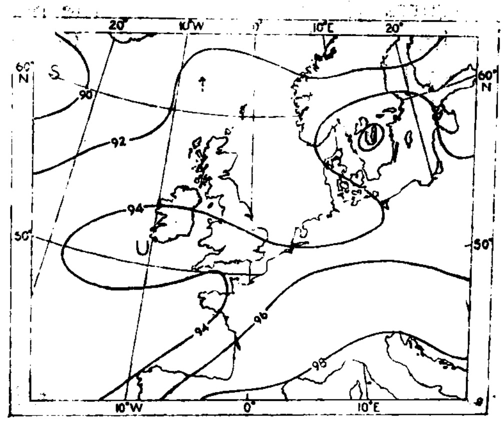

FIGURE 8(*b*)—INSTABILITY INDEX ANALYSIS FOR 0001 GMT, 14 JULY 1962
S 'stable' U 'unstable'

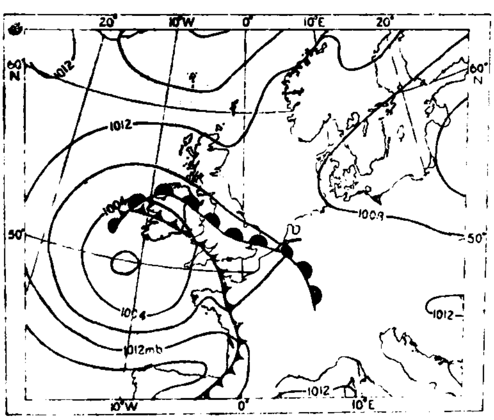

FIGURE 9(*a*)—SURFACE CHART FOR 1200 GMT, 14 JULY 1962

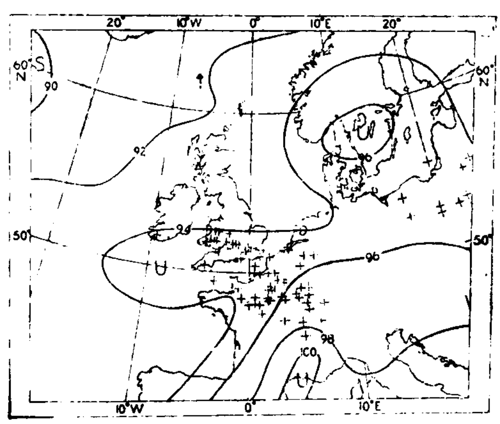

FIGURE 9(*b*)—INSTABILITY INDEX ANALYSIS FOR 1200 GMT, 14 JULY 1962
+ location of sferic reports, 1200–1700 GMT
S 'stable' U 'unstable'

Most of the charts are in pairs, the instability charts being to the right of the corresponding surface charts. Sferics reported between 1200 and 1700 GMT, inclusive, are marked on 1200 GMT instability charts, but no sferics are shown on charts for 0001 GMT. The reason for this is that the index was devised in relation to thunderstorms developing over land on summer afternoons. It can be used as a guide to the possibility of thunderstorms over the sea and to night thunderstorms over the land, but its application to this smaller number of thunderstorms has not been studied in detail.

Figures 4 to 6 illustrate the importance of the area of high index being clearly delineated when the problem is that of determining whether the risk of thunderstorms has passed. At 1200 GMT, on 10 May 1962, a complex depression lying east–west across the British Isles was moving away to the Continent (Figure 4(*a*)). The instability index chart and the sferics in the period 1200–1700 GMT are shown in Figure 4(*b*). The 94 index line was north of the Faeroes, so it is clear that the southward advection by the light 700 mb winds, as the depression moved away eastwards, would be slow to bring more stable air over England.

Figures 5(*a*) and 5(*b*) show the position at 0001 GMT on 11 May. The 94 line has moved to south of the Faeroes but the index remains high over the British Isles. Pressure was rising over the western half of the country and in the *Daily Weather Report* decreasing showeriness was forecast, though with heavy local falls in the south-east in the earlier part of the period. Figures 6(*a*) and 6(*b*) relate to 1200 GMT on 11 May (with sferics for 1200–1700 GMT) and confirm that with no change in the degree of instability a forecast of another day with widespread thunderstorms would have been justified. It may be added that the instability index was as high as 94 over south-east England the next day, but thunderstorms did not develop because cloud from the North Sea reduced the surface temperature rise.

The main advantage claimed for this form of instability index is its usefulness in mobile situations, regardless of whether fronts are involved. Figures 7 to 9 illustrate its value in assessing the degree of instability likely to be developed on a front when it encounters a warm land surface. Between 9 and 13 July 1962, a warm sector crossed the Atlantic and reached our south-west coasts as a partially occluded system. Figure 7 shows successive 12-hour positions of the 94 instability index line from 0001 GMT on 12 July to 1200 GMT on 13 July. An observation at ocean weather station 'D' on the 10th had shown an index at least as high as 95 in the central area of the depression and this level was therefore maintained in the subsequent analysis; an index of 94 was also reached as the frontal instability ridge passed station 'K'. The position at 0001 GMT on 14 July is shown in figures 8(*a*) and 8(*b*). No sferics had been reported over the North Atlantic or the British Isles for several days, but now the instability ridge with an index of at least 94 showed that thunderstorms could be expected over the southern half of England and Wales, though these were not forecast at the time. Figures 9(*a*) and 9(*b*) show the situation by the afternoon of that day.

Figures 10 and 11 illustrate how unexpected the instability pattern may be in relation to the surface isobars. Figures 10(*a*) and 10(*b*) show an area of high index lying across the north-westerly flow over the British Isles at 1200

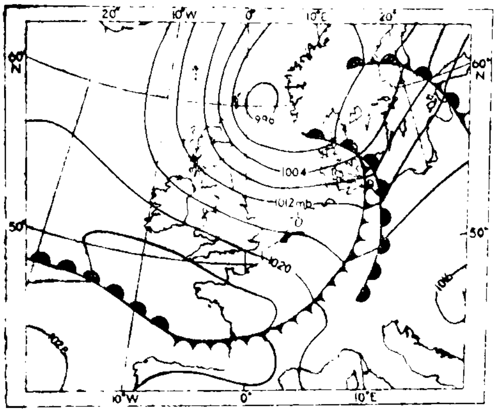

FIGURE 10(*a*)—SURFACE CHART FOR 1200 GMT, 23 MAY 1962

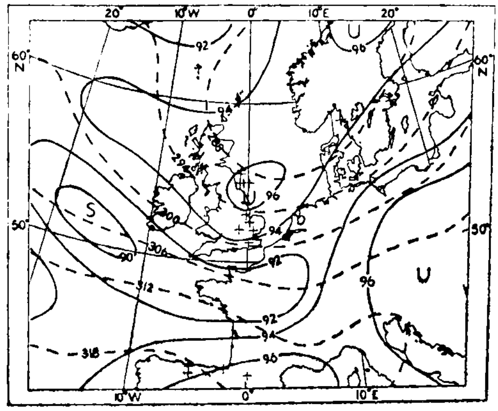

FIGURE 10(*b*)—INSTABILITY INDEX ANALYSIS AND 700 MB CHART FOR 1200 GMT, 23 MAY 1962
+ location of sferic reports, 1200–1700 GMT
S 'stable' U 'unstable'
- - - 700 mb contours in geopotential decameters

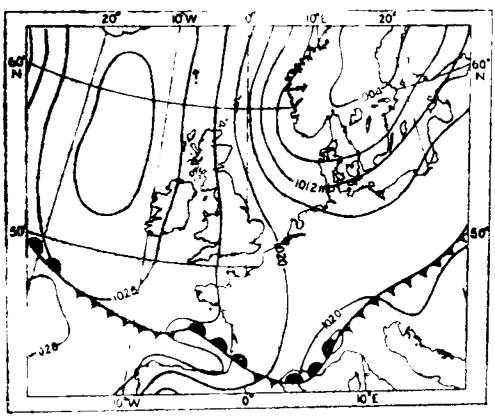

FIGURE 11(*a*)—SURFACE CHART FOR 1200 GMT, 24 MAY 1962

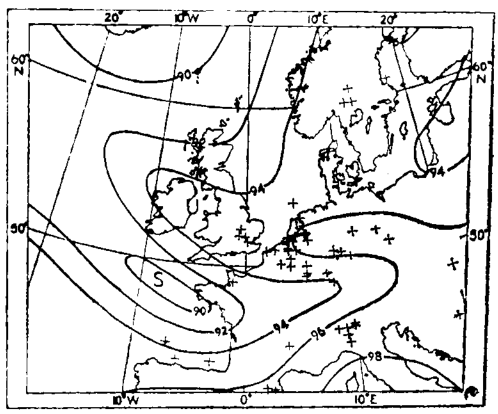

FIGURE 11(*b*)—INSTABILITY INDEX ANALYSIS FOR 1200 GMT, 24 MAY 1962
+ location of sferic reports, 1200–1700 GMT
S 'stable' U 'unstable'

GMT on 23 May 1962. The extension of the instability to the region of ocean weather station 'I' was associated with a depression which filled the previous day. On Figure 10(*b*) the 700 mb contours have been added in order to show the narrowing of the instability ridge which was to be expected as the 94 line moved south over Scotland and remained slow-moving over Wales. Twenty-four hours later the tongue of unstable air extended from Northern Ireland to East Anglia and the air was now much more stable over Scotland, as is seen in Figure 11(*b*). The instability charts suggest that thunderstorms might reasonably have been expected as far north-west as Lancashire but, in fact, they were confined to south-eastern parts of England.

Finally, Figure 12 is included for comparison with the patterns obtained for the Jefferson and Rackliff indices, as published by Jefferson.[4] The main difference in the pattern lies in the absence of the stable area over southern France as depicted by Jefferson.

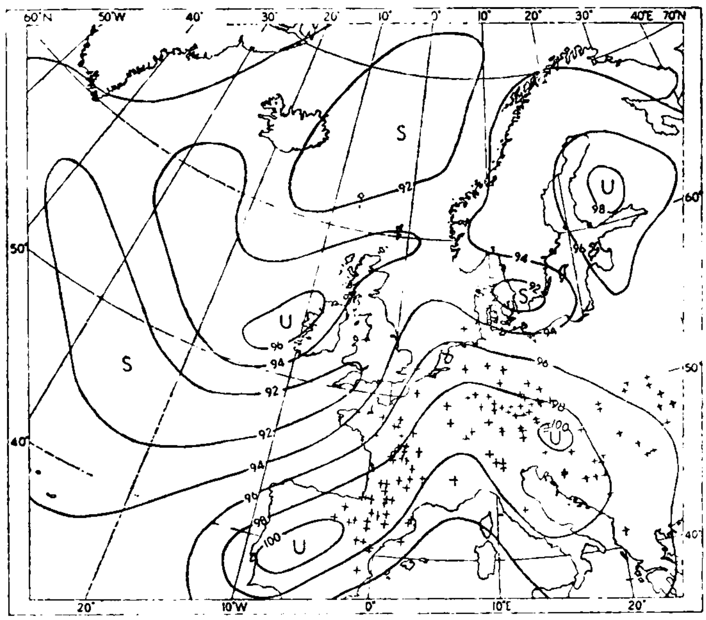

FIGURE 12—INSTABILITY INDEX ANALYSIS FOR 1200 GMT, 18 JUNE 1962

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551.501.42 (048.1):551.508.77:551.577.2

COMPARISONS OF RAIN-GAUGE MEASUREMENTS

By E. R. C. REYNOLDS, Ph.D.

The work of Dr. Poncelet at the Royal Meteorological Institute, Brussels, should be consulted by all who are concerned about the reliability of the readings from rain-gauges. Lawes[1] has done a great service in translating the most important paper[2] into English, though the translation of some of the statistical terms should be corrected. The preliminary work was presented at the Rome meeting of the International Association of Scientific Hydrology[3] and a later paper in the series was published in 1962.[4] Publication of the methods and results has synchronized with the beginning of the extensive World Meteorological Organization rain-gauge comparisons.

The object of Poncelet's investigations has been the comparison of various rain-gauges from national meteorological services to obtain valid reduction coefficients between them. These studies naturally lead to suggestions to improve the instruments and progressively to eliminate their faults.

Poncelet's method was to group the instruments together on a sheltered site in the grounds of the Institute. He gives a model description of the site using maps and photographs. The environs might be more immediately visualized if the screening angles had been shown as well. French, German and British (Meteorological Office 8-inch) gauges were installed in a systematic pattern, according to the instructions of the various meteorological services. These gauges were duplicated, and this was important since it allowed of comparison within a type as well as between types, or, to put it another way, some allowance could be made for effects resulting from the particular location of each gauge as distinct from the characteristics of the instruments themselves. There were also two of the older type of Belgian rain-gauge (installed rather differently from one another) and three of the newer goblet-shaped Belgian gauges (again not strictly replicating each other). On one of the newer Belgian gauges various wind-shields were tested including the Nipher and Alter shields as well as Poncelet's own designs. Daily records were collected for five years. Climatic information was also collected, and the validity of the approach is emphasized in that, although this data was not always collected at the rain-gauge site, nor in the form most relevant to rain-gauge behaviour, it considerably assisted the interpretation of the data.

Poncelet is careful to point out that he is only assessing rain-gauge efficiency relative to a reference gauge, and he suggests that the absolute accuracy of this gauge could be established by experimental or theoretical means. A further contribution on these lines is in fact promised.[4] He also acknowledges that for hydrological water balance studies it is the absolute accuracy of the rain-gauge which must be known. Until this can be established, he advocates the interpretation of the records from rain-gauge arrays by classification according to the climatic conditions associated with the rainfall. Thus the relative defects of the various types of gauge are determined.

In the comparison of rain-gauges, the relation between the total catches for a lengthy period is often derived. Poncelet begins his examination of the data at this point and concludes that under his conditions it took at least five years to achieve reduction coefficients stable to within one per cent. Subsequent analyses are presented to show that the structure of these coefficients is complex and results from interacting factors which sometimes oppose one another. He states that it is out of the question to apply long-term coefficients to individual small storms.

The method of classifying the records to interpret the behaviour of rain-gauges has been considerably developed by Poncelet. Table I shows the classification he used with the relevant chapter numbers of his work.[2] It is designed to examine the relative efficiency of the various instruments in overcoming splashing into or out of the gauge, infiltration through the joints, evaporation from the funnel and from the collecting vessel, condensation in the funnel, site effects, and losses by the Jevons wind effect. In the classification, rainfall intensity is approximated by the size of the daily catch, the insolation causing evaporation after rainfall by the duration of bright sunshine, and the number of wetting and drying cycles by distinguishing between continuous and intermittent rain. By sub-classifying, the effects of many interactions are suppressed, so that, under otherwise homogeneous conditions, the effects of certain environmental factors become apparent. Some information

TABLE I—SUMMARY OF PONCELET'S CLASSIFICATION OF RAIN-GAUGE RECORDS, INCLUDING CLASSIFICATION BY PREVAILING CLIMATE

§ Section number in Poncelet's paper.[1,2] Figures in brackets give number of records.

- UNCLASSIFIED RECORDS (551)
  - YEAR § 5
    - 1952–53, 1953–54, 1954–55, 1955–56, 1956–57.
    - (First two years excluded from other analyses)
  - PRECIPITATION TYPE § 13
    - Rain
    - Snow
      - *Size of collection in millimetres* § 13
        - $<$ 10, 10–19.5, $\geq$ 20
  - SEASON § 5
    - Winter, spring, summer, autumn
  - SIZE OF DAILY RECORD (in millimetres) § 12
    - $<$0.5(167), 0.5–0.95(60), 1–1.95(71), 2–4.95(125), 5–9.95(87), 10–19.95(38), $>$ 19.95(3)
  - MONTHS § 5
    - Dry months ($<$40 mm)
    - Wet months ($>$ 80 mm)
  - SUNSHINE AFTER RAIN § 6
    - $>$ 1 hour bright sunshine (20)
    - ½–1 hour bright sunshine (62)
    - $<$½ hour bright sunshine (72)
    - No subsequent sunshine (271)
      - *Character of rain* § 7 *and* § 9
        - Intermittent (107)
        - Continuous (84)
          - wind direction § 10 (classified in two ways, (*i*) equal numbers per sector or (*ii*) all available records)

	(*i*)	(*ii*)
N–NE	(5)	(9)
E–SE	(5)	(5)
S–SW	(5)	(45)

wind speed at 28 metres (in kilometres per hour) § 11
$<$10 (12,) 10–19(13), 20–29(11), $>$29(5)

W–NW	(5)	(21)

- *Size of daily record (in millimetres)* § 12
  - $<$0.5(27), 0.5–0.95(32), 1–1.95(39), 2–4.95(82), 5–9.95(64), 10–19.95(26), $>$ 19.95(3)
- *Wind speed at* 28 *metres (in kilometres per hour), S–SW winds only* § 11
  - $<$10(24), 10–19(60), 20–29(40), $>$ 29(9)

is lost, of course, since some of the interactions may be of considerable importance. The arbitrary limits of the classes break up a continuous spectrum of variation of the factors, and so a little more information is lost.

Having classified the records, the total catch of each gauge in each class was usually expressed as a ratio of that of one of the new Belgian gauges which was provided with a gauze-covered Nipher shield. Unfortunately this gauge happened to lie on the edge of the array of gauges, but no great objections to its being used as a reference appeared in the figures.

The papers give the merits and demerits of each type of gauge and windshield as revealed by this method, care being taken to evaluate the importance of the findings by applying simple statistical tests of significance.

Using Bernard's figures from rain-gauges in the Congo, Poncelet shows how much can be done to analyse records in the absence of data other than that from the compared rain-gauges. He finds that separate recording of day and night rain may be of considerable value. It was encouraging to find that

To face p. 212

PLATE I—DR. R. C. SUTCLIFFE, C.B., O.B.E., F.R.S.

See page 197

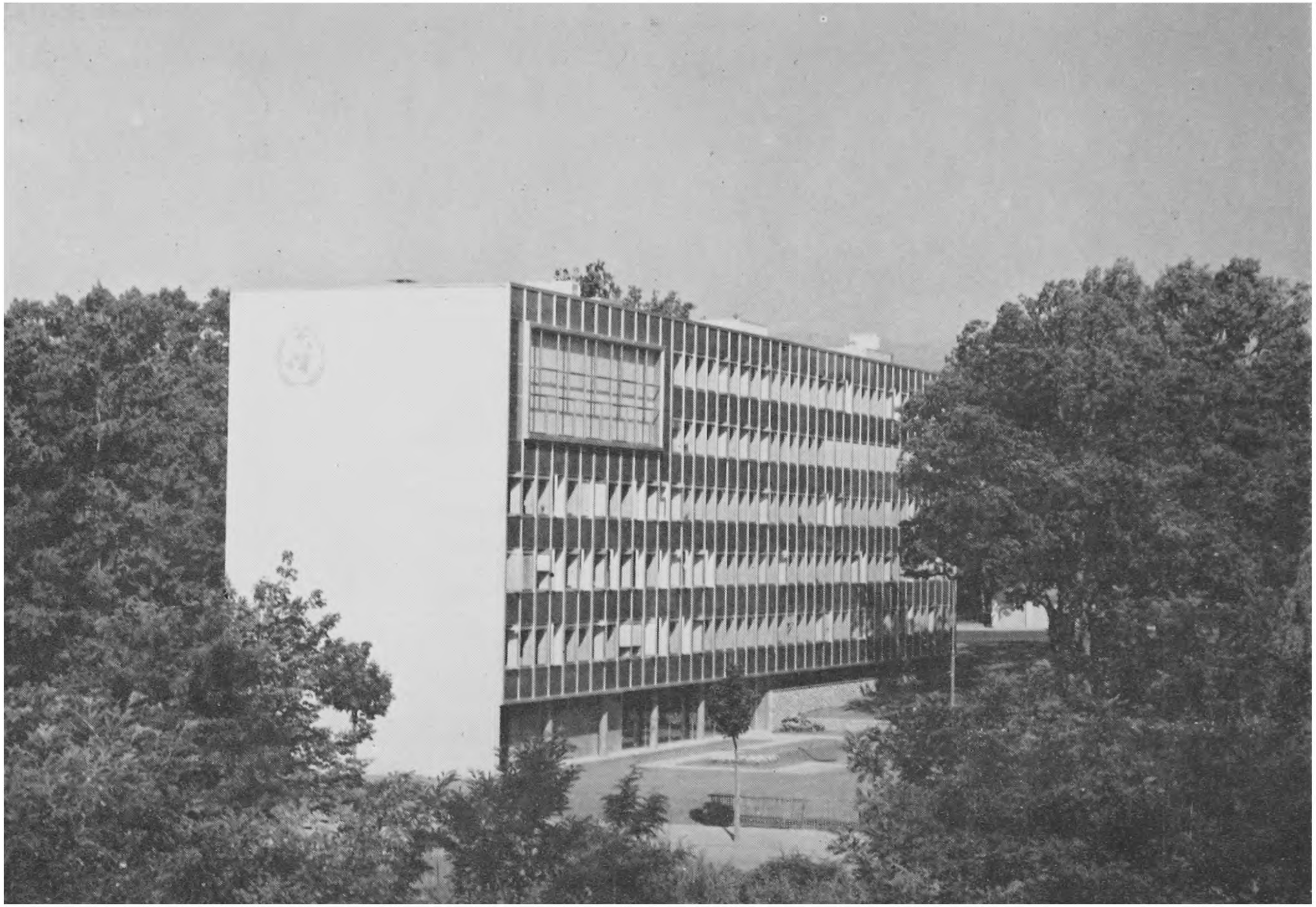

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PLATE II—WORLD METEOROLOGICAL ORGANIZATION HEADQUARTERS IN GENEVA

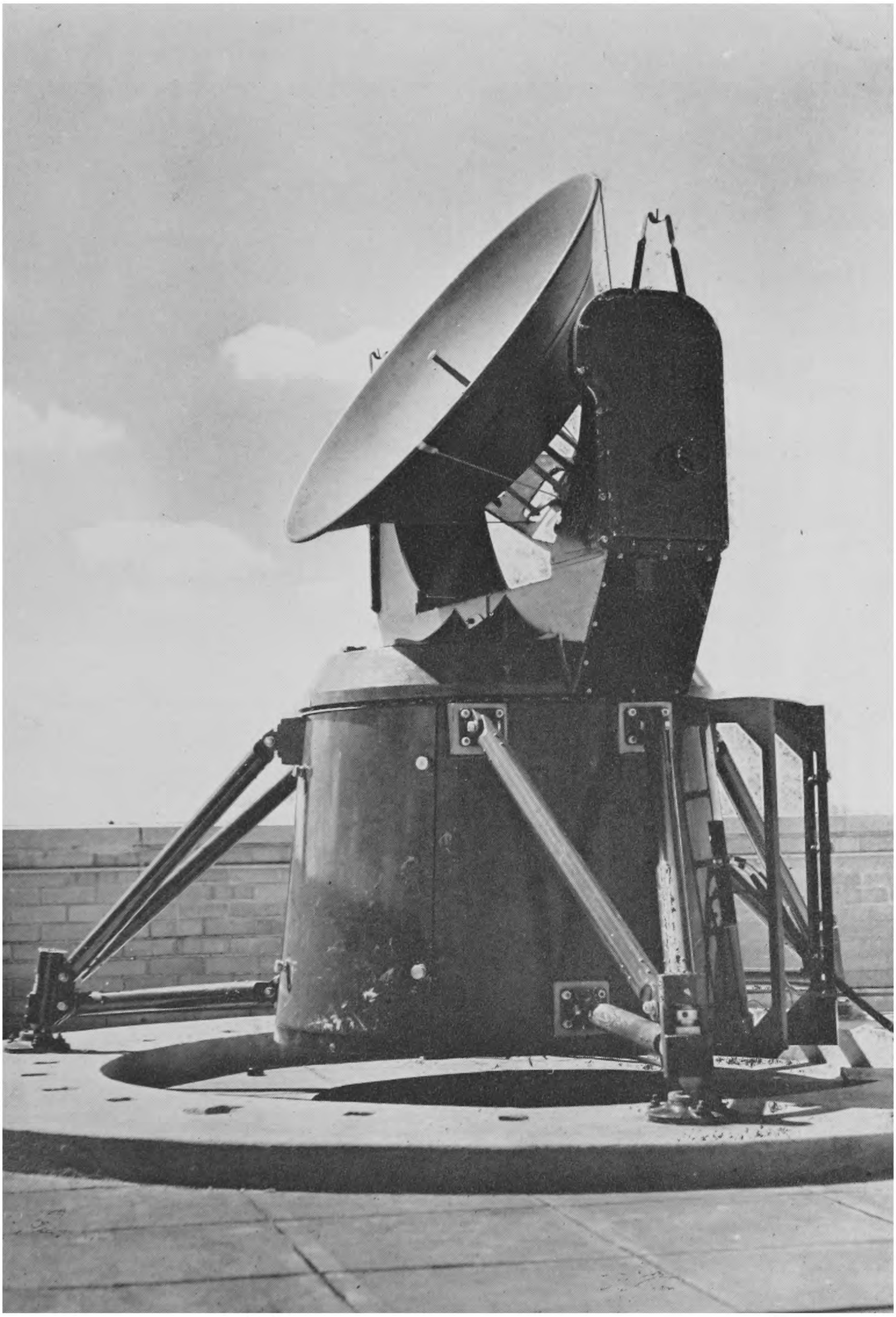

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PLATE III—AERIAL SYSTEM OF DOPPLER RADAR AT PERSHORE

This was the equipment used in the project described on page 213.

To face p. 213

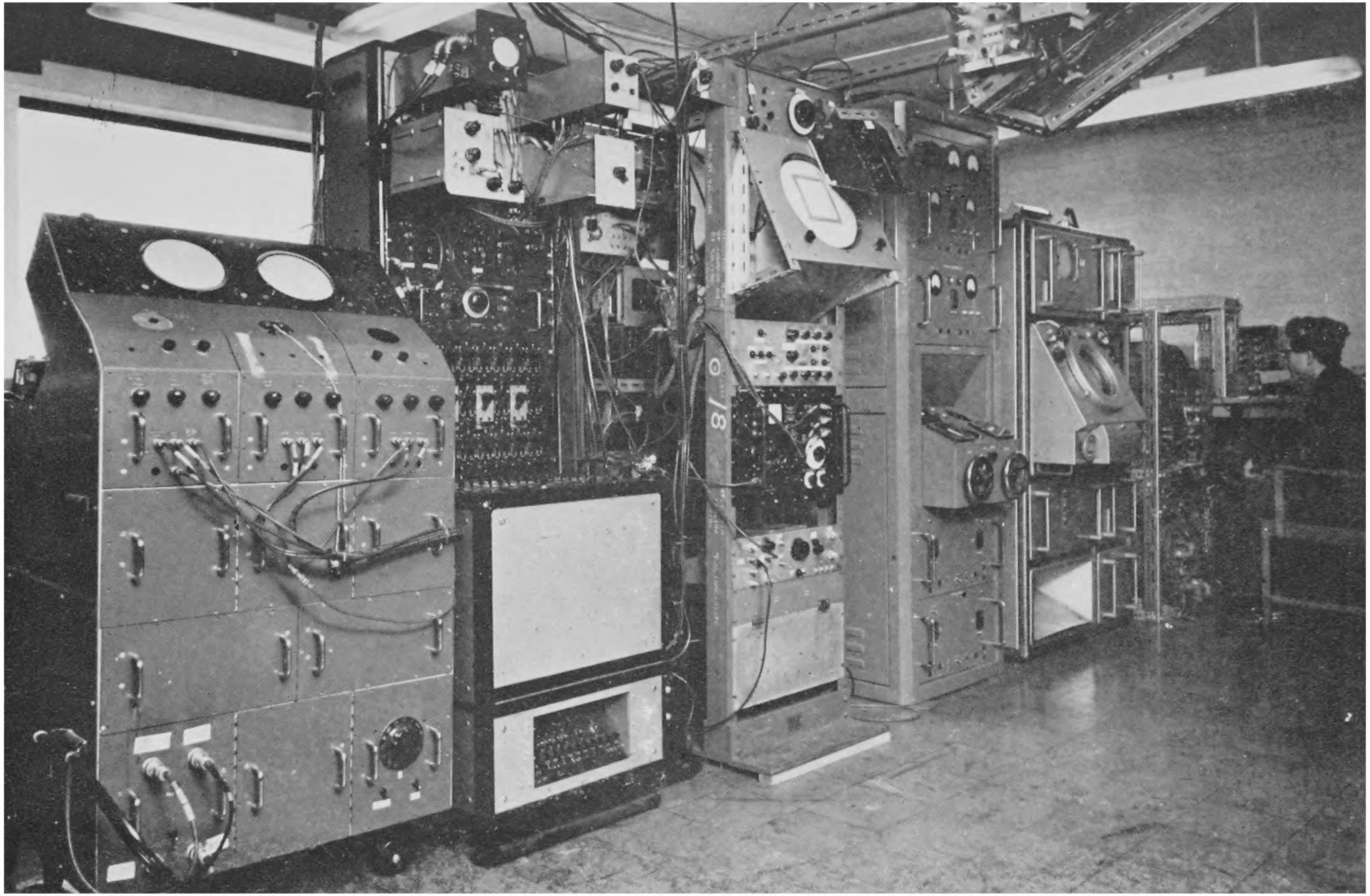

PLATE IV—CONTROL EQUIPMENT AND DISPLAY CONSOLES OF THE DOPPLER RADAR AT PERSHORE

This was the equipment used in the project described on page 213. The radar records from a shower, facing page 276 in Volume 91, 1962, of the Meteorological Magazine, were recorded on the camera (top right) shown in this photograph.

reduction coefficients between gauges in the Congo agreed reasonably well with those in Belgium (after excluding, from the latter records, the figures for months when snow fell).

Perhaps the most interesting contribution which Poncelet makes is an attempt to relate the reduction coefficients between rain-gauges from one year to another by using simple climatic parameters. He stipulates that these parameters should be such that they can be obtained from the simplest weather stations. The two which he uses are the number of days with intermittent precipitation (approximated by subtracting the number of days without sunshine from the number of days with measurable precipitation) and the proportion of the total annual precipitation due to snow and sleet. For a given year, the difference of each of these (E_1 and E_2 respectively) from their mean values over five years, when multiplied by empirical coefficients characteristic of the gauges compared (k_1 and k_2 respectively) and summed, gave a reasonable approximation to the differences of the individual annual reduction coefficients, i.e. $k_1 E_1 + k_2 E_2 = \Delta$, where Δ is the deviation of the reduction coefficient from its mean value. Although Poncelet acknowledges that this is an empirical method, he believes that such interpolation formulae may make it possible to circumvent systematic comparisons over long periods in all climates. It will be interesting to see this technique applied in the future. Certainly, considerable weight is given to the possibility that one day there will become available formulae which will relate the absolute accuracy of rain-gauges to measured climatic conditions.

This work by Poncelet has proved most stimulating to the reviewer in connexion with the comparison of rain-gauge behaviour above trees in a wood near Oxford. It is hoped to expand Poncelet's suggestions in the light of this experience in a communication in preparation.

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551.501.75:551.508.85:551.557

WIND MEASUREMENT BY DOPPLER RADAR

By P. G. F. CATON, M.A., Ph.D.

Summary.—A method is presented for the measurement of upper winds in precipitation conditions by Doppler radar. By combining wind components observed at 10° intervals of azimuth over a wide sector, mean wind speed and direction may be measured at a number of heights simultaneously and the variation of wind both in space and time may be investigated. Observations obtained during the advance of two warm fronts have been analysed. The application of the Doppler technique to the measurement of convergence is examined and preliminary results described.

Introduction.—A recent development in centimetric radar has provided an indication of line of sight velocity of the target through measurement of the Doppler frequency shift in the returned signal. Using a continuous-wave Doppler radar Holmes and Smith[1] have measured a wind velocity of 200 miles/hour in a tornado, but without range information. The meteorological uses of a pulsed Doppler radar providing simultaneous amplitude, range and velocity information have been examined at the Royal Radar Establishment, Malvern, by Boyenval[2] and Probert-Jones.[3,4] By directing the aerial vertically the fall velocities of precipitation particles may be measured. In warm-front rain where the vertical air motions are relatively small, drop-size distributions may be derived. For convective precipitation Probert-Jones and Harper[5] have deduced estimates of the vertical air motion. If the aerial is directed at moderate angles of elevation, the line of sight velocity includes a component of the horizontal wind and measurements of the velocity along different azimuths may be used to evaluate the wind. This paper describes and assesses the method of wind measurement, presents the results obtained during the advance of two warm fronts and also some data on small-scale space and time wind variations observed in the warm air. A similar use of Doppler radar has been suggested by Lhermitte and Atlas.[6]

Examples of records obtained at Pershore, Worcestershire, have recently been published.[5] Although for these examples the aerial was pointing vertically, the method of display was identical with that used in the wind measurements. Briefly, the information is produced in discrete form and displayed as a matrix on a cathode ray tube, each row corresponding to a range interval along the beam of about 150 metres (500 feet), and each column to a velocity interval of 1 metre/second (2 knots). The echo from the scatterers in each range interval and velocity band is summed and presented on the cathode ray tube as intensity modulation. The display is photographed, each picture having an exposure of 5 seconds.

Evaluation of the wind.—In Figure 1 let the horizontal wind at the point of measurement at height z have speed u and direction θ, let the vertical

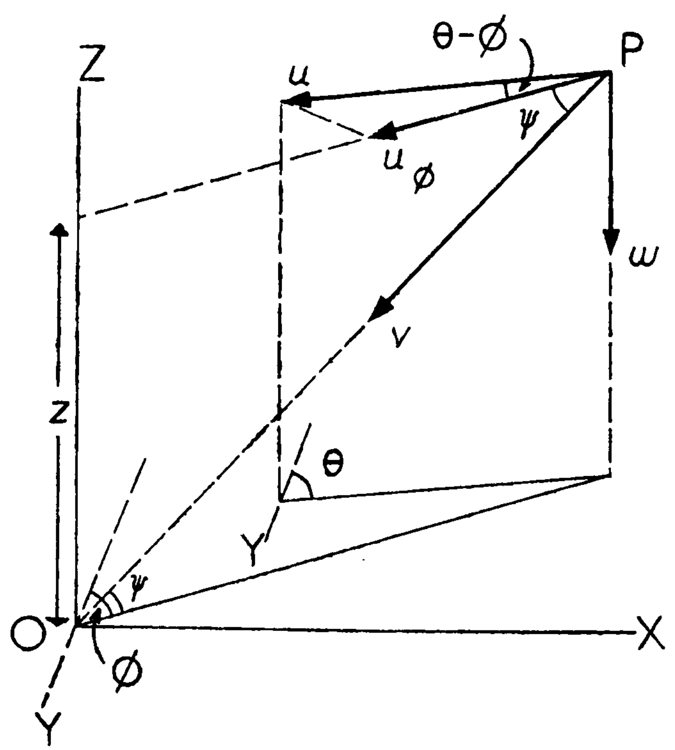

FIGURE 1—DOPPLER WIND EVALUATION DIAGRAM

(downward) velocity of the precipitation particles be w and the radar beam have azimuth and elevation φ and ψ respectively, then, the velocity v, measured towards the radar, is

$$v = u \cos(\theta - \varphi) \cos\psi + w \sin\psi.$$

Hence the component of the wind along the azimuth of the beam, *ue*, is

$$u_\varphi = u \cos(\theta - \varphi) = (v - w \sin\psi) \sec\psi.$$

In order to find the vector wind Probert-Jones[3] combined values of *ue* for two azimuths θ_1 and θ_2, 20° apart, assuming that the wind was the same at the two observation points. This method of computation is, however, very sensitive to small errors in v which arise from the discrete form of presentation, and it is sensitive also to slight variations in wind between the observing points. Probert-Jones was led to averaging values of u and θ for 20° sectors to give the mean wind over a wider sector.

This mean wind over a wider sector can more easily be deduced through considering that individual values of $u\varphi$ are cosine components of u, the value of u and of the angle $(\theta - \varphi)$ being unknown. Reference to cosine tables shows that, provided the sector examined at 10° intervals of azimuth extends both sides of the wind direction θ, the value of u will be accurately given by the mean of the seven largest values of u_φ (corresponding to angles $(\theta - \varphi) \leq 35°$) subject to an addition of 6.5 per cent. If the mean is taken over the five largest values the addition is 3 per cent. Values of θ may next be deduced from individual values of u_φ, $(\theta = \varphi + \cos^{-1}(u_\varphi/u))$, and a mean taken over those for which $u_\varphi/u \leq 0.85$, $(\theta - \varphi) \geq 32°$, the remaining values being more sensitive to error.

The technique does not require the assumption of complete uniformity in wind between observing points. It is assumed that the speed deduced from observations on azimuths approximately along the wind direction applies also to observations at greater angles to the wind, but small differences in speed would often have little effect on the deduced directions. Further advantages are that aberrant values of θ are immediately apparent and may be checked, and that variations through the sequence may be interpreted as the vector variation of wind within the sector. The method thus reveals both the mean wind over the sector and the internal variation, while possessing the practical merits of simplicity, accuracy and ease of error detection.

Observational procedure.—The normal method of operation was to observe at a beam elevation of 30° ($\sin\psi = 0.5$) and at 10° intervals of azimuth over a sector extending at least 60° each side of the estimated upwind direction. Because of the variation of wind direction with height in frontal conditions the sector frequently extended to 180° or more. The time interval between observations was about 10 seconds, a complete sequence occupying between 3 and 4 minutes. At the beginning and end of each series an observation at 90° elevation was made. These vertically-looking measurements provide a direct record of the precipitation particle fall velocities (w), which in general vary with height.

Recordings were made during the advance of two warm fronts, the first on 8 December 1961, and the second on 28 March 1962. On both dates the above sequence of observations was repeated at intervals of about one hour to define the pattern of wind change through the frontal surface. Additional observations were sometimes made at intervals of 3–5 minutes and occasionally at two angles of elevation, 23½° and 53° (sin ψ then had values 0.4 and 0.8), in order to explore wind variations in the warm air above the frontal surface.

At 30° elevation the maximum range normally displayed on the cathode ray tube corresponds to a height of about 5½ kilometres (km). However, the height to which winds can be measured is frequently limited by low signal strength to 3–4½ km. At a height of 3 km the points of observation at 10° intervals of azimuth are 0.9 km apart on the arc of a circle of radius 5.2 km. Observations at different heights along one azimuth are not vertically above one another nor in general directly up or downwind. Further, each observation is a mean of radial velocities over an echoing volume determined by the beam width of the aerial, the pulse length of the transmitter and the time constant of the gating circuit; for elevation angle 30° and height 3 km, the volume has a width of 140 m, a length of approximately 300 m and may extend over a height interval of about 270 m.

Wind observations near frontal surfaces.—The variation of the mean wind over the sector of observation during the advance of the front on 28 March 1962 is shown in Table I.

TABLE I—VARIATION OF MEAN WIND DURING THE ADVANCE OF THE FRONT ON 28 MARCH 1962

Height *km*	Time GMT 1355	1445	1600	1700	1815	1855
	mean wind in degrees/knots					
4.5		262/31				
4.2	264/32	264/30	270/28½	263/34		
3.9	250/32	261/30	272/29½	267/34	284/23½	
3.6	250/32	255/30	272/32	267/33	283/23½	
3.3	254/32	263/30½	275/28	272/30	288/23½	285/23½
3.0	262/33	258/32½	272/27	276/29	285/23	285/27½
2.7	248/32	251/33½	264/31½	277/28	281/21½	284/26½
2.4	227/32	246/34½	253/36½	264/30½	275/22	288/26
2.1	204/30	216/35½	231/38½	246/36	266/24	284/27
1.8	161/32½	197/32	203/40½	218/37	254/29½	268/26½
1.5	162/34	163/32	177/38½	203/40	232/32½	244/29½
1.2	166/35	145/30½	162/38½	185/42	205/36½	211/33½
0.9	162/33	150/31	158/36	166/40	189/36	193/36½
0.6		161/30½	157/34	153/36½	160/33½	169/36½
0.3		171/27½	159/24	145/27	142/26½	142/23½

Observations between the two stepped lines are within the zone of frontal shear.

The boundaries of the frontal zone cannot be precisely defined; the two stepped lines bound observations which appear to be within the zone of strong shear. The shear zone descends at an average rate of 210 m/hr. The speed of advance of the surface front was approximately 50 km/hr, so that the frontal slope may be estimated as 1:240. The vector difference per 300 m height change within the zone of strong shear ranges from 3 to 23 knots with a mean of 13.3 knots. This mean shear, if entirely of thermal origin, corresponds to a local temperature gradient of 7.5°C/100 km. By comparison the mean vector wind difference per 300 m height change in the warm air well above the frontal surface is 2.5 knots.

The mean winds observed during the second frontal situation are shown in Table II. In this case the rate of descent of the shear zone was only about 70 m/hr, associated with a slow rate of advance of the surface front. The two final columns illustrate the short-period fluctuations in mean wind which sometimes occur.

TABLE II—VARIATION OF MEAN WIND DURING THE FRONTAL SITUATION ON 8 DECEMBER 1961

Height *km*	Time GMT 1255	1355	1450	1540	1630	1730	1737
			Mean wind in degrees/knots				
3.3				232/26		218/30½	229/29
3.0		246/27½		231/27		218/31	222/28
2.7		243/26½		228/27½		216/28	222/30
2.4		241/25	235/23½	222/26		216/27½	226/31½
2.1		248/22½	238/23½	218/23½	228/25½	211/27	219/30½
1.8		240/17	234/23	219/21½	222/27½	208/25½	219/29½
1.5	245/–	233/20	232/25	225/22	226/28	219/26½	219/25
1.2	251/17	227/22	218/26	228/25½	229/29½	225/29½	220/26
0.9	201/32	207/23½	215/25	227/25½	228/27	224/28	225/29½
0.6	177/39	184/32	195/30½	196/26½	201/24½	211/33	211/33½
0.3	166/27½	162/30	167/29	166/32	169/27	171/27½	176/29½

Observations between the two stepped lines are within the zone of frontal shear.

Accuracy of wind evaluation.—An individual value of v (or w) derives from the observation of echo in one or more velocity channels centred 1 m/sec apart. The relative strength of the signal between channels permits estimation of the mean v in units of 0.25 m/sec. The spread of recorded velocities is due mainly to the variations of wind within the echoing volume and to the range in precipitation fall velocities. Above the 0°C level in warm-front rain the particle fall velocities are very uniform at about 1–2 m/sec. Below the melting level the fall velocity of the raindrops has a wider span, from 2 to sometimes 9 m/sec, which results in greater error in estimation of mean values. From consideration of the several factors and from the values recorded by two observers working on the same data, it is estimated that the standard error of measurement of the derived values of u_φ is 0.25 m/sec at heights above the 0°C isotherm and 0.75 m/sec below.

Above the 0°C level the standard error in mean values of u should not exceed 0.1 m/sec from measurement causes alone, since each mean is derived from a set of seven values of u_φ. However, the actual variations within each set exceed expectation, undoubtedly because of small but real variations of u between observing points. From the general run of values it is deduced that the total standard error in mean values of u is about 0.2 m/sec (0.4 knots) and, accordingly, values have been recorded to this accuracy. Assuming a wind speed of 30 knots (the approximate average for the days of measurement) the standard error of measurement of u_φ corresponds to a standard error in θ of 1.5°. However, the observed average standard deviation in θ, excluding abnormal values (see a later section), is 2.1°. The expected standard error in a mean of eight values of θ is therefore 0.8°, equivalent to a vector of 0.4 knots.

The total standard error of the vector mean winds in Tables I and II is thus estimated as $\sqrt{((0.4)^2 + (0.4)^2)} \simeq 0.6$ knots. The variations between values in those Tables are therefore considered to be largely real.

Wind variability.—The Doppler radar provides a possible means of investigating space and time variations in wind. It must be stressed that the short analysis which follows refers to two dates only and to levels above warm-front surfaces ($2\frac{1}{2}$–$4\frac{1}{2}$ km above ground). A principal aim is to illustrate the types of variation which may be studied.

(i) *Wind variations within an echoing volume.*—Even if the wind were uniform in space a spread of velocities would occur during a single observation of v due to measurement over a finite beam and to variations in precipitation fall velocity. However, these causes account for only a small proportion of the velocity spread normally observed at any one range. The major cause of velocity spread is wind variations within the echoing volume and these are found to have standard deviation 1.3 m/sec (2.5 knots). Part of this is due to turbulent fluctuations, and part to changes in the horizontal wind across the vertical extent of the echoing volume.

Subsequently in this section the term 'wind' will refer to the average value over an individual echoing volume and 'mean wind' to the mean over the sector of observation of wind values centred at one height.

(ii) *Wind variations between echoing volumes at one height.*—As indicated in the previous section the observed standard deviation of derived angles θ (2.1°, excluding abnormal values, see paragraphs below) exceeds that expected (1.5°) solely due to errors of measurement of the components u_φ. The excess indicates the existence of real variations either of u or θ or both between echoing volumes. The standard deviation of these variations was deduced to be 1.5°, equivalent to a vector of 0.40 m/sec (0.8 knots) for a wind speed of 30 knots. This value for the wind variability, derived from observations along azimuths broadly at right angles to the wind, compares closely with that of 0.38 m/sec (0.7 knots) deduced from the run of values of u_φ observed on azimuths close to the wind direction.

A typical series of observations of $u_\varphi \cos\psi$ and derived values of θ is shown below:

Azimuth (deg)	130	140	150	160	170	180	190	200	210	220	230	240
$u_\varphi \cos\psi$ (m/sec)	$-8\frac{1}{2}$	-6	-3	0	$2\frac{1}{4}$	5	7	8	10	$11\frac{1}{2}$	$12\frac{1}{2}$	$13\frac{1}{2}$
θ (deg)	257	255	252	250	251	249	251	256	255	256	–	–
Azimuth (deg)	250	260	270	280	290	300	310	320	330	340	350	
$u_\varphi \cos\psi$ (m/sec)	$13\frac{3}{4}$	$14\frac{1}{2}$	14	$12\frac{3}{4}$	12	$10\frac{3}{4}$	$8\frac{1}{2}$	$6\frac{1}{2}$	$3\frac{1}{2}$	$1\frac{1}{2}$	$-\frac{1}{2}$	
θ (deg)	–	–	–	–	–	259	257	257	254	256	258	

It will be seen that while the values of θ for azimuths 130–140°, 200–220° and 300–350° are grouped about a mean of 256° with standard deviation 1.4°, those for azimuths 150–190° have a mean of $250\frac{1}{2}$°. This behaviour by five adjacent values covering a distance span of about 5 km is considered to indicate a real difference of wind from the remainder of the sector and will be termed an abnormality. In general it is not possible to be sure whether it is the wind direction or speed or both which vary, but in this case the abnormal observations are along azimuths nearly at right angles to the wind and give information on direction rather than speed.

In a sample of 30 sectors at different times and heights ($2\frac{1}{2}$–$4\frac{1}{2}$ km) 9 showed entirely random variations in the θ values. The remaining 21 showed 23 abnormalities in θ values extending over sub-sectors of 20° or more. Frequently an abnormality at one height occurred in modified form 300 m above or below. The sizes of the sectors involved ranged from 20° to 90° azimuth with a mean of 42°, corresponding to a linear distance of 3.8 km at height 3 km. The abnormalities in wind direction varied from 3° to 14° with a mean of 6.4°, equivalent to a vector change of 3.4 knots. Overall, the abnormalities covered 22 per cent of the θ values surveyed. However, this percentage was higher for the azimuth sector 140°–230° (32 per cent) than for the sector 310°–360° (14 per cent), and it is possibly significant that the southerly sector was directly downwind (10 miles) of the Malvern Hills on the day concerned.

Observations were occasionally made at two beam elevations, 23½° and 53° (sines 0.4 and 0.8), to investigate wind variations along radial axes. At a height of 3 km the pair of observations at one azimuth are 4.6 km apart. The root mean square vector difference in wind between observations at one azimuth was close to that for observations along circular arcs. This suggests that results derived from the more numerous circular arc observations are representative of both axes. The over-all picture of wind variations in a horizontal plane on the dates concerned is therefore of random fluctuations of about 1 knot and systematic deviations of 2–5 knots over regions a few kilometres across; the latter are perhaps particularly associated with hills.

(iii) *Wind variations over short time intervals.*—On both dates series of observations were made in quick succession to investigate wind variations over short time intervals. For one period, 1819–1837 GMT, 28 March, 1962, during which wind variations above the frontal zone appeared to be essentially random in character, the root mean square (r.m.s.) change in wind component (*ue*) at an individual height and azimuth is shown in the left portion of Table III. The root mean square changes in mean wind direction and speed at an individual height are given in the right section of the same Table.

TABLE III—ROOT MEAN SQUARE CHANGES IN INDIVIDUAL WIND COMPONENTS AND IN MEAN WIND DIRECTION AND SPEED FOR VARIOUS TIME INTERVALS FROM 1819 TO 1837 GMT, 28 MARCH 1962

Time interval *minutes*	No. of pairs of 'components'	R.m.s. change of 'component' *knots*	No. of pairs of mean wind	R.m.s. change in direction *degrees*	R.m.s. change in speed *knots*	R.m.s. vector change *knots*
4	88	1.35	5	2.2	0.75	1.15
7	175	1.35	12	2.2	0.7	1.1
11–14	162	1.5	11	2.4	0.8	1.25
18	76	1.35	5	2.3	0.9	1.3
Values arising solely from errors of evaluation		0.35		1.2	0.7	0.85

Significant changes occurred both in individual wind components and in mean wind direction. During a second period (8 December 1961) much larger fluctuations were observed both in individual components and in mean wind, e.g. root mean square vector changes in mean wind of 2.8 knots over 7–9 minute intervals, 3.9 knots over 18–25 minutes and 5.1 knots over 37–40 minutes. The latter values compare closely with those derived by Durst[7] from observations of smoke puffs at comparable heights.

Measurement of convergence.—With the accuracy of measurement of velocity given by the Doppler radar it seems possible that a measurement of convergence can be obtained by summing the radial components of wind observed throughout a 360° rotation. It is possible that a single summation will be substantially affected by purely local air motions since the area examined (e.g. 85 km² at height 3 km) is rather small for this type of measurement, but repetition of the observations may indicate systematic trends associated with larger-scale phenomena. If wind component observations are made at 10° intervals of azimuth

$$2\pi r \frac{\Sigma u_{\varphi}}{36} = \pi r^2 D,$$

where D is the convergence (+*ve*) or divergence (—*ve*) and r is the radius of the circle of observation at height z. It is assumed that the wind component varies linearly between 10° points and that changes are negligible within the time required for a 360° rotation.

An initial test, using wind observations corresponding to the first column of Table I, gave values of convergence as shown in Table IV. Computation was not possible outside the height range indicated, as echo was not continuous throughout the 360° rotation.

TABLE IV—VALUES OF CONVERGENCE AND VERTICAL VELOCITY AT 1355 GMT, 28 MARCH 1962

Height *km*	Convergence sec^{-1} $\times 10^{-5}$	Increment of vertical velocity in 300m layer *cm/sec*	Vertical velocity at top of layer *cm/sec*
3.3	7.8	2.4	35.0
3.0	−1.2	−0.4	32.6
2.7	15.1	4.5	33.0
2.4	3.9	1.2	28.5
2.1	9.2	2.7	27.3
1.8	24.2	7.3	24.6
1.5	43.1	12.9	17.3
1.2	14.7	4.4	4.4

Value of vertical velocity in last column assumed zero at 1.05 km.

Three of the four largest convergence values occur immediately below the zone of strong wind shear. The increment in vertical velocity within layers 300 m deep is calculated and also the total velocity assuming, for convenience, that the velocity at 1.05 km is zero. This assumption is of course unlikely to be valid. The maximum vertical velocity of 35 cm/sec seems essentially reasonable. However, too much reliance should not be attached to the absolute value which may, in this instance, have been considerably affected by small inaccuracies in the setting of the velocity zero and the measurement of w (the fall velocity of the precipitation particles). Errors from these causes are systematic in assessments of convergence and precautions to minimize them must be taken with great care. The method shows considerable promise and further measurements are planned.

Discussion.—The Doppler radar provides a possible means of measuring in precipitation conditions both the mean wind at different heights and times, and the variations of wind over horizontal distances of a few kilometres and over time intervals of a few minutes. Each individual observation by Doppler radar is of a component of the wind averaged over an echoing volume which very approximately is a 200 m cube. Above the 0°C level in frontal precipitation the estimated standard error purely of measurement is about 0.25 m/sec. Through sampling several volumes at each height a mean wind may be derived, the limit of accuracy being set by the inherent variability of the air motion.

By comparison a wind measurement by conventional radar is an average over a height interval of about 400 m along the path of a single balloon and the standard error of measurement is about 1 m/sec. Further interesting features of a Doppler technique are that individual component measurements are effectively instantaneous in time and that, if wind changes are being studied, frequent measurements are possible at precisely repeatable heights. It should be stressed, however, that a Doppler radar cannot measure wind speed and direction with uniform accuracy throughout the sector of observation; measurements near the wind direction accurately indicate the speed but give less reliable information of direction, whilst measurements at right angles to the wind accurately indicate direction.

The limitations of the Doppler technique are the requirement for precipitation over a substantial sector around the radar and the moderate height to which observations may normally be made (with this particular radar 3–5 km in light or moderate precipitation). The unambiguous range of velocity display (a function of radar wavelength and pulse-repetition frequency) is 19 m/sec (37 knots), although it is possible to investigate components of one sign up to twice the above value. However, in strong wind situations it would be more convenient to work at a beam elevation of 60°. Wind measurement would be slightly less accurate but observations to a greater height might be possible since ranges of detection are shortened. By contrast if the winds are light at all levels, use may be made of a facility which converts the velocity channels to 0.5 m/sec intervals.

The application of the Doppler wind technique to the measurement of convergence appears most promising and may permit estimation of the vertical motion associated with fronts, and a study of the variations in space and time which perhaps are associated with the rainfall variations frequently observed. A further possibility is the investigation of vertical motions associated with gravity waves induced by hills.

In conclusion the distinctive features of Doppler wind measurement may be summarized as:

(i) requires steady precipitation over the sector of observation,

(ii) when looking cross-wind an instantaneous measurement of wind direction may be obtained,

(iii) wind speed or direction at a fixed point may be measured at short time intervals (every 5 seconds if necessary) over a long period during which the standard of measurement is unchanged. This compares favourably with smoke puffs, which can be followed for only a few minutes and only in clear skies, and with metal foil, which spreads rapidly in the vertical,

(iv) mean wind direction and speed over a sector of observation may be measured at repeatable heights every few minutes, and may be used, for example, to reveal the detailed pattern of wind change through a frontal zone,

(v) being a radial component, is immediately usable in an assessment of convergence.

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FOURTH CONGRESS OF THE WORLD METEOROLOGICAL ORGANIZATION

By C. W. G. DAKING, B.Sc.

The Fourth Congress of the World Meteorological Organization (WMO) was held in the Palais des Nations, Geneva from 1–27 April 1963. It was attended by representatives of 102 Member States or Territories, by observers from 3 non-member countries, and by representatives of 25 other international organizations. The Congress was presided over by M. André Viaut, Director of the French Meteorological Service, acting in this capacity for the second time. The delegation of the United Kingdom was led by Sir Graham Sutton, Director-General of the Meteorological Office, who was assisted by Mr. C. W. G. Daking, Mr. B. M. Day (Air Ministry F.1), Instructor Captain J. A. Burnett R.N., Director of the Naval Weather Service, Admiralty, and Mr. D. H. Anderson of the Foreign Office. Miss J. M. Prior acted as secretary to the delegation.

As is customary, the large agenda, consisting of over 50 items, was dealt with by means of three working committees although in the event, it would have speeded up the work to have had an additional committee to deal with Technical Co-operation matters, especially as these took up a great deal of the time of the Administrative and Finance Committee.

For the purposes of this article, attention has been focused on the major items dealt with by each committee.

Legal and general questions.—In accordance with a decision made at Third Congress, the Executive Committee (EC) reviewed the WMO Convention during the period 1960–62 and submitted its proposals for revisions to Fourth Congress. Much of the work involved had been done by a Working Group of the EC of which the Director-General was a member. In addition to the amendments proposed by the Executive Committee, several members submitted amendments in accordance with Article 28(*a*) of the Convention. Much of the time of the Legal and General Committee was taken up on this item, discussion being lengthy because of the diverse views adopted towards the changes proposed and the consequent difficulties of obtaining principles and texts which were acceptable to a substantial majority of the Committee.

Two amendments which had an easy passage concerned Article 13(*c*)—composition of the Executive Committee. It had been expected that a move towards a larger EC would be made and although several delegations pointed out that a larger Committee might be somewhat less efficient and effective, there was no real opposition to increasing the number of members from 18 to 21. Similarly, the proposal by Australia that no Region should have less than 2 members found general acceptance. The Resolution putting forward these two changes to Article 13(*c*) was passed by Congress with 81 votes in favour and no votes against.

The document submitted to Congress concerning other amendments to the Convention ran to 24 pages of text and to 11 pages in the Appendix containing 19 proposed amendments. Of these, 5 failed to receive 71 votes in favour, the number necessary for their adoption by Congress and subsequent embodiment in the Convention.

Fortunately, the Articles of the WMO Convention are self-contained and the adoption of new texts for 14 Articles will not cause confusion. However, in view of the legal difficulties encountered during the discussion in Committee, it was decided to establish a Working Group of Congress to make a further study on the form and wording of the Convention. This Group is to report to the President of WMO 18 months before Fifth Congress so that its recommendations may be examined by Members in time for them to comment within the 6 months time limit provided for in Article 28(*a*) of the Convention. The United Kingdom was invited to designate an expert to serve on the Working Group and it is probable that the Foreign Office will make the nomination.

Substantial amendments were made to the General Regulations of the Organization. Proposals for these emanated from the Executive Committee and from Members. Some concerned procedural matters, such as voting by correspondence. The regulations concerning the convening of and agenda for sessions of constituent bodies were completely rewritten. Far reaching changes were made in the languages section, since it was decided that in addition to English and French, Russian and Spanish shall be working languages of the WMO. This means that interpretation and documentation in four languages will be required at sessions of Congress, the Executive Committee, Technical Commissions and some of the Regional Associations. The financial and other implications are considerable, but it must be conceded that the use of four languages (when required) will contribute to a better understanding of written texts and a greater clarity in oral presentations. The burden on countries which 'host' sessions, however, will be very greatly intensified.

Somewhat contrary to expectations Congress was not confronted with a serious problem with regard to invitations to constituent bodies to meet in various countries during the Fourth Financial Period. Several Commissions had received more than one invitation. Only one, the Commission for Maritime Meteorology was without an invitation and budgetary provision was made for that Commission to meet in Geneva at the Headquarters of the Organization if necessary.

Technical questions.—By far the most important matter dealt with on the technical side was the question of Meteorological Satellites and the associated subjects of World Weather Watch and Network Development.

Discussion centred around the First Report of WMO on the Advancement of Atmospheric Sciences and their Application in the light of developments in Outer Space, and the reports of the EC Working Groups on Research Aspects and Artificial Satellites. The concept of a World Weather Watch was generally commended as an exciting development ultimately leading to a World Weather Service. It would be composed of the national and international efforts of Meteorological Services in a co-ordinated plan for the making of observations, their communication to National, Regional and World Centres and the processing of analyses and prognoses and their distribution to those Services which desire them. But an accelerated effort to acquire additional conventional data is necessary in order to achieve maximum benefit from data from meteorological satellites and for this reason considerable attention is to be paid to network development during the Fourth Financial Period. Congress confirmed the approval in principle given by the Executive Committee to the development plan for world-wide networks established by the EC Working Group on Networks. While recognizing that the primary responsibility in establishing and operating observing stations rests with Members, Congress agreed that the WMO should assist Members in completing the observation programmes at existing island and continental stations listed in the plan in cases where such assistance is requested and the need for it is clearly demonstrated. In addition, Congress agreed that the Organization should prepare a detailed plan to enable the remainder of the plan i.e. new island stations, ocean weather stations, automatic weather stations and so on to be completed by 1974. Priority is to be given to areas between 50°S and 65°S.

In view of the need for increasing attention to be given to scientific and technological developments Congress established an Advisory Committee to the Executive Committee whose main tasks will be to advise on all the scientific aspects of the objectives given in United Nations General Assembly Resolutions on Outer Space and on major operational problems relating to these Resolutions. In addition, the Committee will advise on training and education at all levels and on the co-ordination of the scientific activities of the constituent bodies of WMO especially those relating to metetorological satellites. The Committee will be a WMO body and will maintain close contact with other organizations active in the science of meteorology and related disciplines; for this reason it will contain members who can present the views of the International Council of Scientific Unions (ICSU). Reports of the Advisory Committee will be made available, as appropriate, to Members and to Technical Commissions.

Congress decided that before a complete international programme for improving the world weather observational and forecast system (World Weather Watch) could be adopted, a comprehensive study should be carried out with special reference to:

(i) an analysis of national requirements to be placed on the system and the advances in technology that should be utilized to meet these requirements, and

(ii) an overall plan for observational methods and networks, communications systems, processing centres, data distribution and other essential functions of such a system. It requested the Executive Committee to arrange for the study to be completed by mid-1965.

So that the work outlined above could proceed and be properly co-ordinated it was decided to establish a Planning Unit in the Secretariat with the following duties:

(*a*) To assist in the development of the detailed global plan for the World Weather Watch.

(*b*) To provide support to the WMO Advisory Committee and other WMO bodies concerned with outer space questions.

(*c*) To assist in the preparation of reports and supply of information as required by the United Nations (UN) and its agencies.

(*d*) To review continuously the possibilities of obtaining financial assistance for implementation of global plans.

With regard to the structure and terms of reference of Technical Commissions the only aspect that gave rise to discussion and indeed dissension was the terms of reference of the Commission for Hydrometeorology. Several countries were violently opposed to the acceptance by WMO of any aspect of the subject which impinged on pure hydrology. Others pointed out that it was unsatisfactory for there to be divided responsibility for hydrology, that UN had looked to WMO to co-ordinate international aspects and that WMO should not shirk the task.

Terms of reference were finally agreed in Plenary after some two hours of discussion. The main changes from those proposed by the Technical Committee were the substitution of 'hydrometeorology' for 'hydrology' wherever this was possible so the that emphasis was transferred from hydrology to hydrometeorology.

Lengthy discussion also took place regarding the name of the Commission. A large majority disliked the awkward title Hydrological Meteorology and finally Hydrometeorology was adopted.

It was agreed that there was a need for WMO to take a more active part in the planning of and participation in international oceanographic projects particularly to ensure co-ordination of meteorological programmes on fixed oceanographic stations and the compliance of such programmes with WMO procedures. The Intergovernmental Oceanographic Commission (IOC) of UNESCO had already expressed a wish for close collaboration with WMO.

It was necessary, therefore, for WMO to take part in all IOC meetings; later a joint WMO/IOC working group might have to be set up. It was also agreed that IOC should be represented at meetings of relevant WMO bodies. A Resolution including all these ideas was accepted by Congress.

There was considerable support for a proposal that more must be done to promote Antarctic Meteorology including the work of the International Antarctic Analysis Centre (IAAC). The IAAC is making analyses and prognoses as far north as 30°S and can therefore be considered as a Southern Hemisphere Analysis Centre. It was agreed that the IAAC was an important activity and that WMO should find means of ensuring its successful operation.

An Australian proposal to create a Standing Committee for Antarctica was agreed—its members to be representatives of Members of WMO which are contracting parties to the Antarctic Treaty. Agreement of the Antarctic Treaty States meeting in consultative assembly is to be obtained to this proposal before it is implemented by WMO.

There was protracted discussion on the question of units to be used for reporting wind speed in meteorological messages for international exchanges. Most delegates favoured the use of m/sec but others, including the U.K. delegation and International Civil Aviation Organization (ICAO) and Intergovernmental Maritime Consultative Organization (IMCO) representatives pointed out that such use would lead to undesirable difficulties and might contribute to accidents. Congress decided that the introduction of m/sec be postponed pending further consideration of the subject with ICAO and IMCO and that, in the meantime, the existing practice of using knots in coded messages will be continued.

Administrative and financial questions.—The time of the Administrative and Finance Committee was mostly devoted to two items, Maximum Expenditure for the Fourth Financial Period and Technical Co-operation. Much of the discussion was centred on two points, whether WMO should have a Technical Assistance Programme of its own and the Operational and Technical Development Fund, both being closely associated with the need to develop National Meteorological Services and world-wide networks and communications. It was decided to establish a fund for development purposes not provided for under Expanded Programme of Technical Assistance and the Special Fund (UN sources) and an amount of 1.5 million U.S. dollars was agreed on the understanding that a plan for the use of the fund, including procedures for its management and operation should first be worked out by the Executive Committee and the Secretary-General and then submitted to Members for their approval.

It was necessary to increase the size of the Secretariat considerably. Sections for Research and for Training were provided for in the Technical Division and the Telecommunications and Networks Section was expanded. A new post of Assistant Secretary-General was made with the duties of supervising and co-ordinating the work of the Technical and Technical Co-operation Divisions. Reference has already been made to the setting up of a Planning Unit in the Secretariat (see under Technical Questions)—this unit will be responsible directly to the Secretary-General.

The maximum expenditure approved by Congress for the ordinary budget of the Organization for the Fourth Financial Period was $5,373,581, a sum which is nearly twice that approved for the years 1960–63. The conclusion is that the Members decided that in order to make progress with necessary developments, especially those arising from activities placed upon the WMO by the UN General Assembly, the means must be provided both in staff and in money.

There was the customary long debate on proportional contributions. Some countries wishes to retain the existing scale but the majority desired a further move towards the UN Scale which places considerably increased contributions on the U.S.A. and the U.S.S.R. Ultimately it was decided to adopt a scale which is a mean of the existing scale and the 1962–64 UN scale. This increases the U.K. contribution from 67 units to 68 units and that of the U.S.A. from 215 to 274 units. The U.K. contribution is about 6 per cent of the total and is the third largest.

Congress decided that funds should be provided, from the International Meteorological Organization (IMO) Fund and the General Fund, to finance a lecture to be known as the IMO lecture. This lecture would be delivered by an acknowledged expert at each Congress and would take the form of a review of progress in a branch of meteorology or an account of some new advance in the science. The text of the study would be published by the Organization and the actual lecture would be a shortened version of the text.

Congress confirmed the recommendation of the Executive Committee that it was desirable for the Presidents of Technical Commissions to attend sessions of Congress. It was further considered that when these Presidents were not included in their national delegations to Congress, then their travel and subsistence expenses should be paid by the Organization.

Elections.—There were two candidates for the Presidency, Dr. A. Nyberg of Sweden and Mr. M. F. Taha of the United Arab Republic. Dr. Nyberg was elected by 52 votes to 37. Dr. E. K. Fedorov and Mr. Luiz de Azcărraga were nominated for the posts of First and Second Vice-President. Mr. Luiz de Azcărraga was elected First Vice-President.

The outgoing President, M. André Viaut (France) was voted by acclamation to the first electoral seat on the Executive Committee, and Dr. F. W. Reichelderfer (U.S.A.) was similarly appointed to the second seat. There were 20 candidates for the remaining 10 seats. Out of 88 votes cast in the first ballot the Director-General obtained 54—the next highest number of votes received by any one candidate was 6. The following were elected to the remaining 9 seats: F. A. A. Acquaah (Ghana); N. A. Akingbehin (Nigeria); M. Ayadi (Tunisia); G. Bell (Federal Republic of Germany); A. Garcia (Ecuador); W. J. Gibbs (Australia); P. R. Krishna Rao (India); J. Van Mieghem (Belgium); and M. F. Taha (United Arab Republic).

Appointment of the Secretary-General.—The Executive Committee in Resolution 47 (EC-XIV) expressed complete confidence in Mr. D. A. Davies and recommended to Fourth Congress that he be re-appointed for a further period of four years. There was no other candidate and Mr. Davies was reappointed amidst considerable enthusiasm from the Congress.

The Palais des Nations, Geneva, is as one would expect, ideal for large international gatherings. Apart from the spaciousness and magnificence of the Assembly Hall which is superbly furnished, and the high standard of comfort in the committee rooms, delegates have easy access to post and telegraph, and banking facilities in addition to a restaurant, cafeteria, and several coffee bars. Provision was made for distribution of documents in the conference section where an enquiry desk and travel bureau were also available. As usual, the organization was excellent and the Secretary-General and his staff, both permanent and temporary, are to be congratulated. The translators, typists and duplicating staff in particular deserve special mention as the Congress considered no less than 192 documents, excluding working papers of the three Committees.

NOTES AND NEWS

Seminars on high-level forecasting

A further seminar on forecasting for turbine-powered aircraft operations was held in Bangkok from 20 November to 7 December 1962 under the joint auspices of the World Meteorological Organization (WMO) and the International Civil Aviation Organization (ICAO). Rear Admiral S. Vesa-Rajananda, Director-General of the Thai Meteorological Department, presided. The seminar was similar in its general scope to those previously held in Cairo and Nicosia in 1961.[1] Work in Bangkok was concerned with analysis and forecasting for high-level air routes over tropical and subtropical areas from 65°E to 135°E and 25°N to 15°S.

Over the greater, oceanic, part of this region data are pitifully few, and very little is known, climatology apart, of the true character of the weather systems which occur; and as far as the upper wind and pressure fields are concerned, even the climatology leaves something to be desired. With good reason then, Professor N. E. Laseur of Florida State University, who directed the seminar, warned participants at the outset not to expect cut and dried solutions to be offered to their problems. The programme of work consisted of analysis and forecasting for two selected synoptic situations, each extending over a few days, map discussions, lectures and exercises. The lectures, given by Professor Laseur and chief analysts D. V. Rao, Senior Meteorological Officer, Calcutta, and D. H. Johnson, Climatological Research Division, Bracknell, covered many topics of general interest in aviation forecasting and of specific local interest. Analysis and forecasting techniques successfully used in other parts of the tropics were discussed and there were specific exercises on isogon, streamline and isotach analysis, low-latitude contour analysis, thunderstorm forecasting, differential analysis, and the derivation of prediction equations for statistical forecasting of upper winds. In addition, several of the participants gave talks on their local forecasting problems. These included for example: the description of an objective method of forecasting fog at Mingaladon, by U Thu Ta (Burma); and an account of the squall phenomena, misnamed 'Sumatras', which form in the Malacca Straits and travel eastwards, by W. H. Smith (Meteorological Office, Changi).

The seminar was held in pleasant surroundings at the Headquarters of the Thai Meteorological Department, and the participants, who came from countries ranging from Iran to the Philippines, and from Korea to Australia, were indebted to the Thai Director-General and his staff for affording every facility and courtesy. The problems met in organizing seminars of this kind might be said to vary inversely with the Coriolis parameter, and the hard work put in on this occasion by the co-Directors, Dr. H. Voss (ICAO) and Mr. N. L. Veranneman (WMO), was well appreciated by all concerned.

D. H. J.

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METEOROLOGICAL OFFICE DISCUSSION

Recent advances in seismology

The last Meteorological Office discussion of the winter season was held at the Royal Society of Arts on 18 March 1963.

Dr. H. M. Iyer opened the discussion with a talk centred around a brief summary of the main problems in earthquake seismology, the modern seismological instrumentation, microseisms, and some recent work on digital analysis of seismograms.

Earthquake seismology is concerned with the collection of data from past earthquakes and using the information for the study of the source, magnitude and mechanism of fresh earthquakes. The identification of multiple pulses from an earthquake enables the study of the macroscopic structure of the earth. The seismograph responds to earth movements which are generally converted into analogue electrical signals by some kind of transducer and either recorded photographically by a mirror–galvanometer arrangement or amplified electronically and recorded on strip-chart, magnetic tape or paper tape. Seismographs are now available for a variety of purposes, from working on the deep ocean bottom to operating on the moon's surface.

A very careful study of microseisms using the latest instruments and techniques is slowly unravelling the nature of the waves. It is now fairly well understood how the ocean, coupled with the solid material below, acts as a resonant system and forces like atmospheric turbulence and ocean waves can excite the system. However, extensive study is required to understand fully the relationship between meteorological forces and microseisms. Digital analysis of earthquake surface waves and displaying the change of spectrum with time in the form of energy contours in a frequency–time diagram, promise to give valuable information on the dispersion characteristics of the earthquake surface waves.

The discussion after the talk was mainly regarding the usefulness of microseisms in meteorology.

METEOROLOGICAL OFFICE NEWS

Arts and Crafts exhibition.—The Bracknell Metorological Office Social and Sports Club held its first Arts and Crafts exhibition on 5 May 1963. There were over 200 entries and the quality of the exhibits was very high. The classes covered sewing, embroidery, knitting, cookery, woodwork, rug-making, art, photography and horticulture. Lady Sutton kindly presented the prizes and remarked that she did not realize there was so much talent amongst the staff. It is hoped to make this an annual event.

HONOURS

The following awards were announced in the Birthday Honours List on 8 June 1962:

C.B.E.

Professor P. A. Sheppard, Chairman of the Meteorological Research Committee.

O.B.E.

Dr. R. S. Murgatroyd, B.Sc., A.M.I.E.E., Senior Principal Scientific Officer, Head of the Meteorological Reseach Flight, Farnborough until 4 March 1963.

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METEOROLOGICAL OFFICE M.O. 738

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SOME AERIAL EXPLORATIONS OF COASTAL AIRFLOW

By J. FINDLATER

Introduction.—Several descriptive accounts of sea-breeze fronts and their penetration inland have been written, [1,2,3] deduced mainly from analyses of plan-view charts and surface autographic records. Unusual cloud structures associated with the sea-breeze front have been described by sailplane pilots and others [4,5,6] but their explorations have necessarily been confined mainly to the zone of rising air close to the sea-breeze front and, so far as is known, no detailed temperature and moisture content measurements have been made across these zones in this country.

The structure of sea breezes and their associated convergence zones has considerable bearing on a number of important forecasting problems, e.g. formation of showers in the convergence zone,[7] penetration of sea air inland leading to relatively low maximum temperatures, and the amount of cloud in the coastal strip. It was with the aim of exploring the upper structures of sea breezes and, in particular, of their convergence zones that this investigation was undertaken.

Organization.—The plan adopted was to concentrate the maximum observational effort into a small area on a few chosen days rather than to accumulate relatively fragmentary data distributed widely in space and time. The line chosen for the investigation was the 52 nautical mile route from White Waltham to the Owers lightship (50°37′N 00°41′W).

Primary observations were made in the air from a Chipmunk aircraft, equipped with an electrical resistance psychrometer and an aneroid barometer, and manned by a pilot and a meteorologist. The aircraft flew along the selected line between White Waltham and the Owers lightship at varying heights, measured above mean sea level, whilst taking dry- and wet-bulb temperature measurements approximately every two minutes. Cruising air-speed was 85–90 knots. Visual observations of cloud, haze, smoke and smoke drift were also made. On the south-bound leg of the flight the aircraft was flown at 1500 feet until either the sea-breeze convergence zone or the coast was passed, when it gradually descended close to the sea surface to make a near-vertical sounding in the vicinity of the Owers lightship, 10 nautical miles offshore. The flight path followed thereafter was dependent on the position of the sea-breeze front as indicated by readings on the south-bound flight and observations of cloud, haze and smoke drift which might reveal the limit of the sea air. The flight path was also influenced by flight regulations concerning airways and controlled airspace.

The scope of the investigation was planned to contain the more vigorous springtime sea breezes which penetrate more than 35 miles inland and influence developments up to at least 5000 feet, but during investigations in 1961 the organization proved adequate to study the weak and shallow sea breezes in autumn.

The investigation was planned for a maximum of two selected days per month, on week-days only. To supplement the aircraft observations made during the period 1330–1515 GMT, a number of ground stations co-operated by making pilot balloon observations and recording other relevant data. Pilot balloon ascents to 5000 feet at 1300, 1400 and 1500 GMT were made from White Waltham, Farnborough, Odiham, Wormley, Cocking, Thorney Island and Tangmere; in addition the London Weather Centre maintained a radar watch over the route to record precipitation echoes from 1300 to 1700 GMT. The locations of these stations relative to the investigation line are shown in Figures 1 and 2. All the official observing stations listed, and also Wormley,

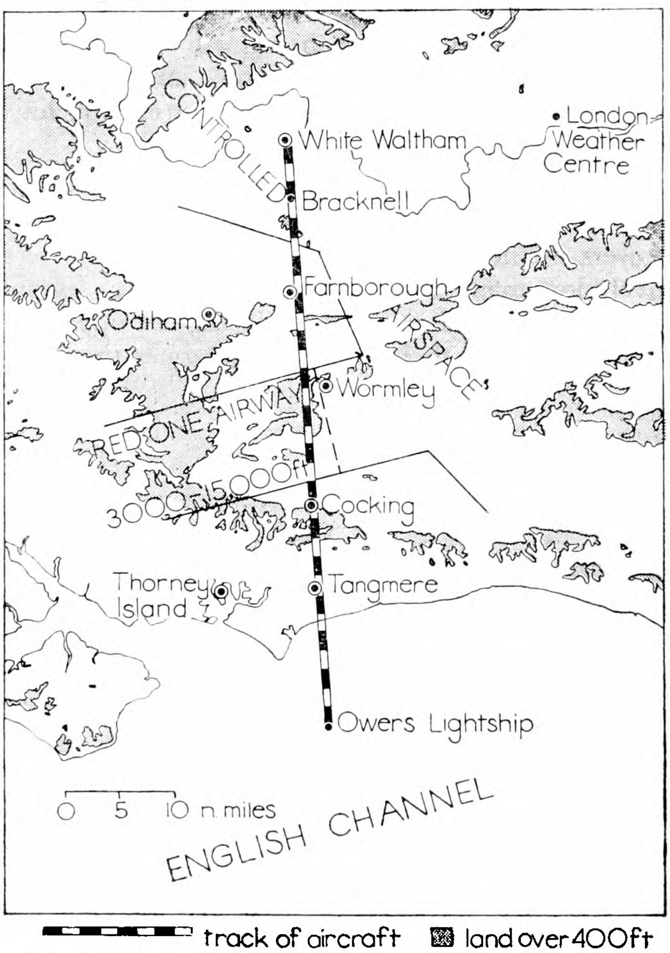

FIGURE 1—LOCATION OF CO-OPERATING STATIONS
Pilot balloon stations are ringed.

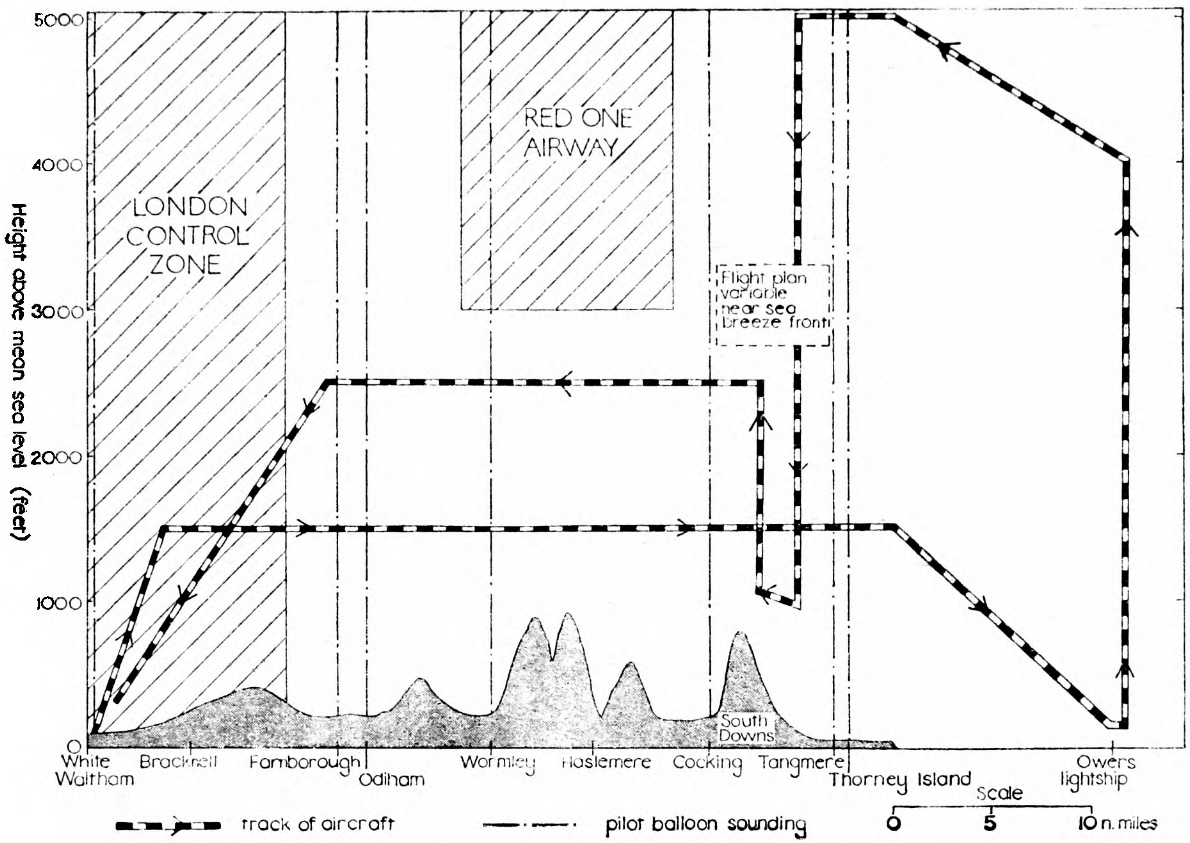

FIGURE 2—FLIGHT PLAN AND POSITIONS OF PILOT BALLOON SOUNDINGS

manned by staff of the National Institute of Oceanography, provided normal hourly observations and autographic records.

On days which were considered suitable for investigation all participants were informed by telephone by 0900 GMT and subsequently carried out the programme noted above. During 1961, operations were only possible during the autumn when sea breezes were weak and fickle; four investigation days were declared and on the first three full programmes were carried out. On the fourth day flight observations were cancelled owing to aircraft unserviceability and only the wind programme was carried out.

Instrumentation.—

Ground stations.—For the surface and pilot balloon observations standard observing equipment was used at the stations listed above and shown in Figure 1.

Aircraft.—The aircraft was equipped with a Meteorological Office aircraft electrical resistance psychrometer Mk 1b calibrated in degrees Fahrenheit and readable to one half degree. Readings from this instrument were corrected for errors due to ambient pressure, speed and position, in addition to the normal instrument errors, and subsequently converted to degrees Celsius. An aircraft aneroid barometer Mk 2b was also carried. Dry- and wet-bulb temperatures were measured against height on an ordinary aircraft altimeter set to sea-level pressure and check readings were taken at various levels.

Aircraft temperature readings taken on take-off and landing were compared with simultaneous measurements made at White Waltham with an Assmann psychrometer. During ascents and descents vertical speeds were limited to 300 feet per minute to prevent errors due to the lag of the instrument.

Analysis.—

Day 1—29 *August* 1961—*hot with south-easterly winds, no sea-breeze development.*— The afternoon was hot and cloudless with stable air flowing from the south-east. Surface temperatures exceeded 30°C over the northern part of the investigation route during the afternoon, although a stable layer at 1500-2000 feet limited the penetration of dry thermal convection from the surface. With moderate on-shore winds no sea-breeze effect could be detected—the cool sea air warmed up rapidly within a few miles of the coast. Cross-sections of temperature, moisture content and wind are shown in Figures 3 and 4. Of particular interest is the very warm air over the sea at levels between 500 and 2500 feet, and the cooler air over the South Downs and the hills around Haslemere. A trajectory of the sea air at about 1000 feet showed that the air had been over France some six hours earlier and that the extreme warmth of the air could be accounted for by heating over the continent.

A streamline of the vertical displacement likely to be followed by the sea air is shown in Figure 3 and marked upon it are temperatures which would result from adiabatic changes. These temperatures are consistent with the recorded temperatures and they suggest that the temperature patterns were due to adiabatic changes brought about by topography. The pattern of moisture content lends support to this suggestion.

Each of the pilot balloon stations released balloons at 1300, 1400 and 1500 GMT but of these only those at 1400 GMT are plotted on cross-sections. Little coastal effect is noticeable in this case, but the increase of wind with height up to 1000 feet just north of the South Downs is very well marked.

Day 2—31 *August* 1961—*light east to north-easterly wind, weak sea breeze.*—This day was cloudless also but the surface temperatures were about 5°C cooler than on 29 August in mid-afternoon and the light winds inland were directed mainly offshore. A stable layer was again based at 1500–2000 feet with dry thermal activity below this level. A well marked, although weak, sea breeze set in at Tangmere shortly after 1300 GMT and reached a little to the north of the South Downs before dying out in the evening. At the onset of the sea breeze at Tangmere the surface wind, previously 080 degrees 8 knots, veered to 140 degrees 3 knots and then steadily changed to 160 degrees 10 knots; the dew-point rose by 2°C as the sea air arrived. Cross-sections of temperature, moisture content and wind are shown in Figures 5 and 6.

The sea-breeze convergence zone was made readily visible by a wall of smoke from south-coast towns and numerous field fires. The smoke tracked inland and kept close to the ground in the stable south-easterly sea breeze and changed direction abruptly at the sea-breeze front; easterly to north-easterly winds on the north side of the front sheared the smoke to the west while at the same time it was carried aloft to form a relatively thin wall of about one mile in horizontal extent at 1200 feet. In the stable layer the smoke, considerably thinned, stretched back towards the coast in a tenuous layer eventually overlying the sheet of warm air offshore.

On this day both the temperature and moisture patterns showed that the sea air was twice as deep over Tangmere as it was a few miles out to sea. At 10–12 miles offshore, however, the air was a little cooler and considerably moister up to heights of about 2000 feet than it was just offshore, where subsidence would most probably have been taking place. Wind profiles showed little or no on- or off-shore flow except at Tangmere where the balloon sounding at 1400 GMT showed a marked sea breeze up to 1500 feet with the maximum speed just above the surface, and return flow seawards from 1500 to 3000 feet. Neither of these effects was noticeable at Cocking.

Day 3—19 *September* 1961—*moderate south-westerly winds, weak sea breeze.*—This was a cloudy day with large amounts of altocumulus and altostratus aloft. Temperatures of 22°C produced small cumulus overland at 2000–2500 feet in the fairly moist air spreading in from the south-west. A sea-breeze effect was indicated at Tangmere by the backing of the surface wind to 210 degrees at approximately 1400 GMT and the growth of a zone of deeper cumulus a little way inland. The relevant cross-sections are shown in Figures 7 and 8.

The air over the sea was completely clear of low cloud except for one tenuous lenticular patch of stratus with top at 400 feet lying some 4 nautical miles south-east of Selsey Bill. The position and approximate size and shape of this cloud are shown inserted into Figure 7 as also are the convergence zones indicated by cumulus grouping. The lenticular patch was stationary over the period for which it was observed, about 30 minutes, but it is difficult to visualize the mechanism whereby it persisted. No deviation from course was made to explore this interesting cloud or the surrounding air.

As soon as the air from the sea crossed the coast, fragments of cloud formed at 500 feet and the base lifted rapidly to become 1000 feet over Tangmere, while at the same time the cloud grew into cumulus quite different in size and organization from that inland. Thin veils of pileus cloud overlay the cumulus in the early stages of growth, in a similar fashion to the case reported by

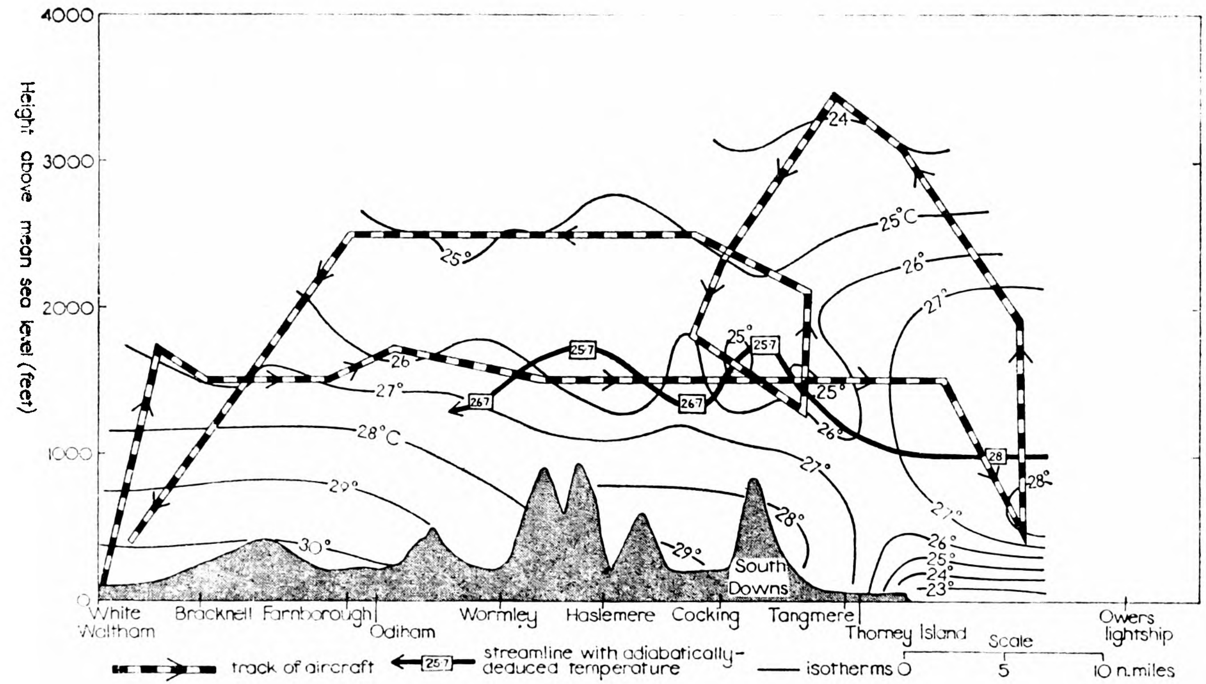

FIGURE 3—ANALYSIS OF DRY-BULB TEMPERATURE, 29 AUGUST 1961, AT APPROXIMATELY 1430 GMT

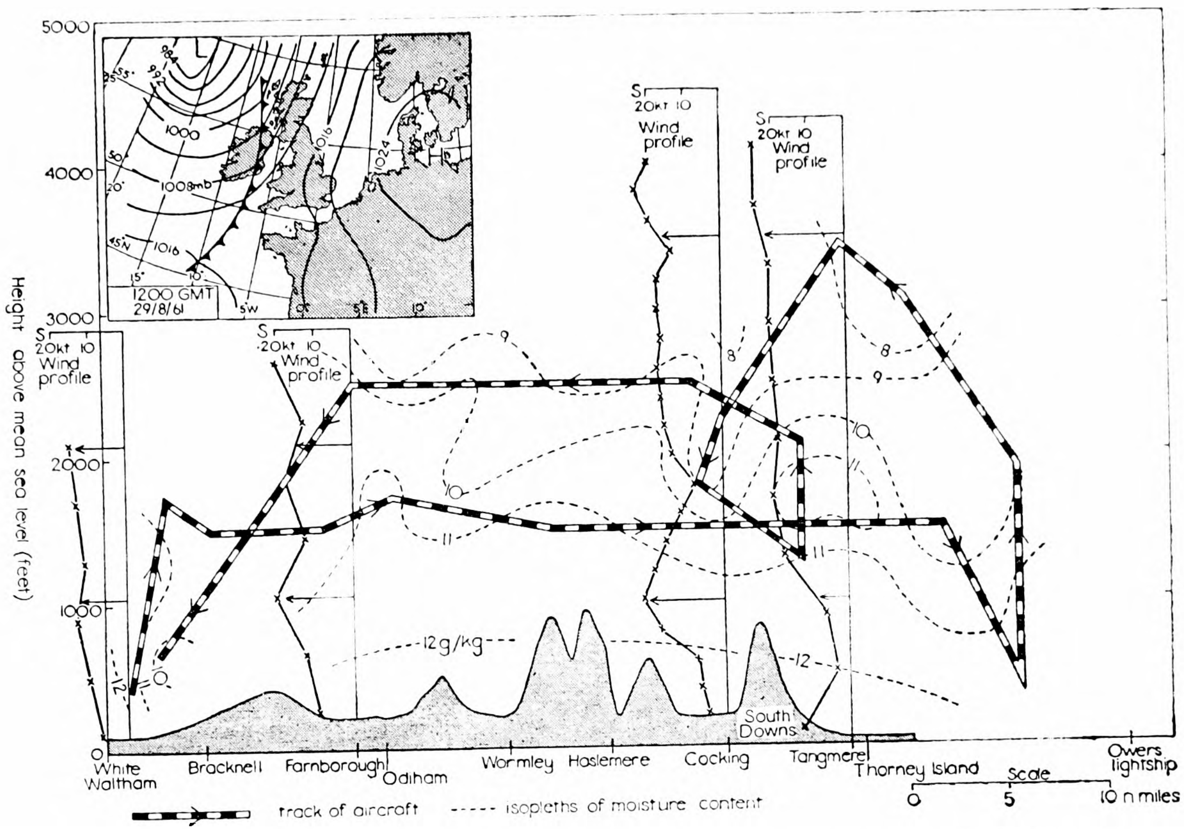

FIGURE 4—WIND PROFILES AND MOISTURE CONTENT ANALYSIS, 29 AUGUST 1961, AT APPROXIMATELY 1430 GMT

Inset shows the synoptic situation at 1200 GMT.

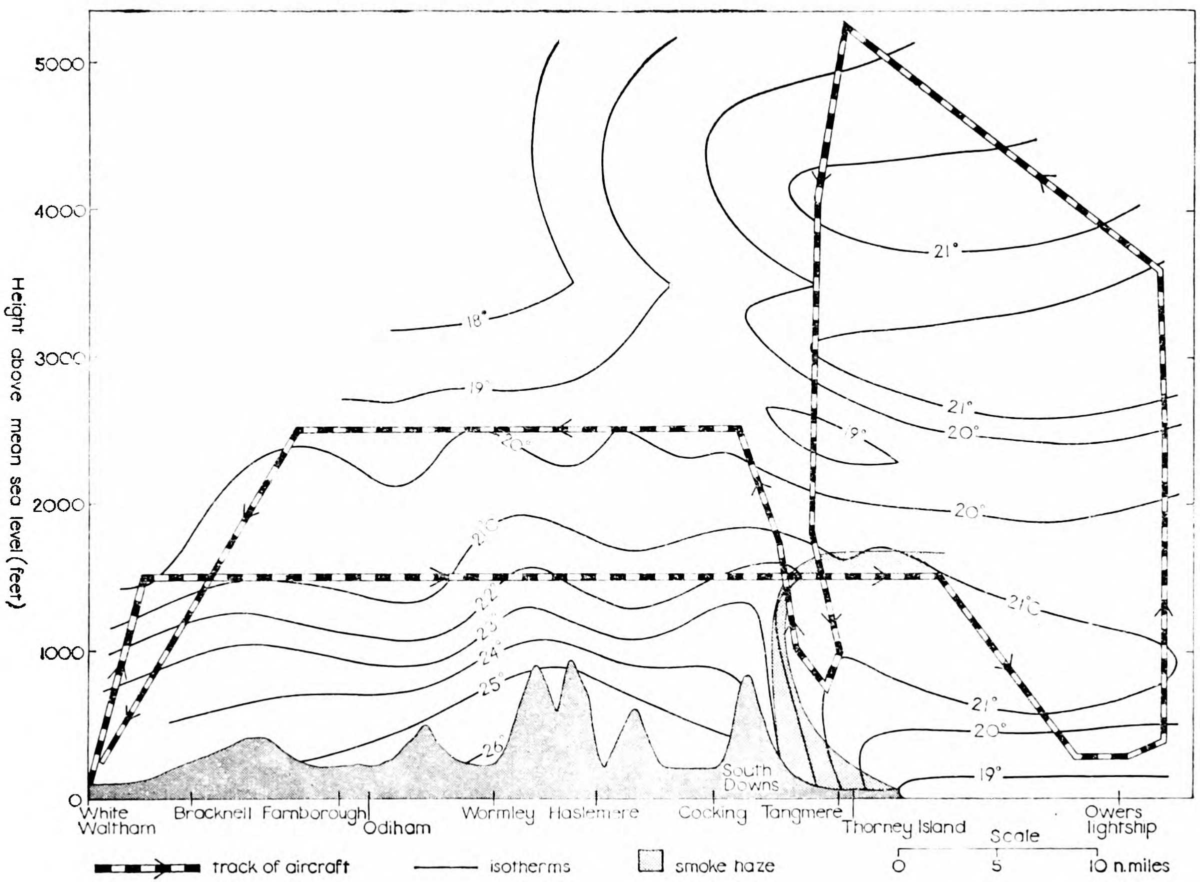

FIGURE 5—ANALYSIS OF DRY-BULB TEMPERATURE, 31 AUGUST 1961, AT APPROXIMATELY 1430 GMT

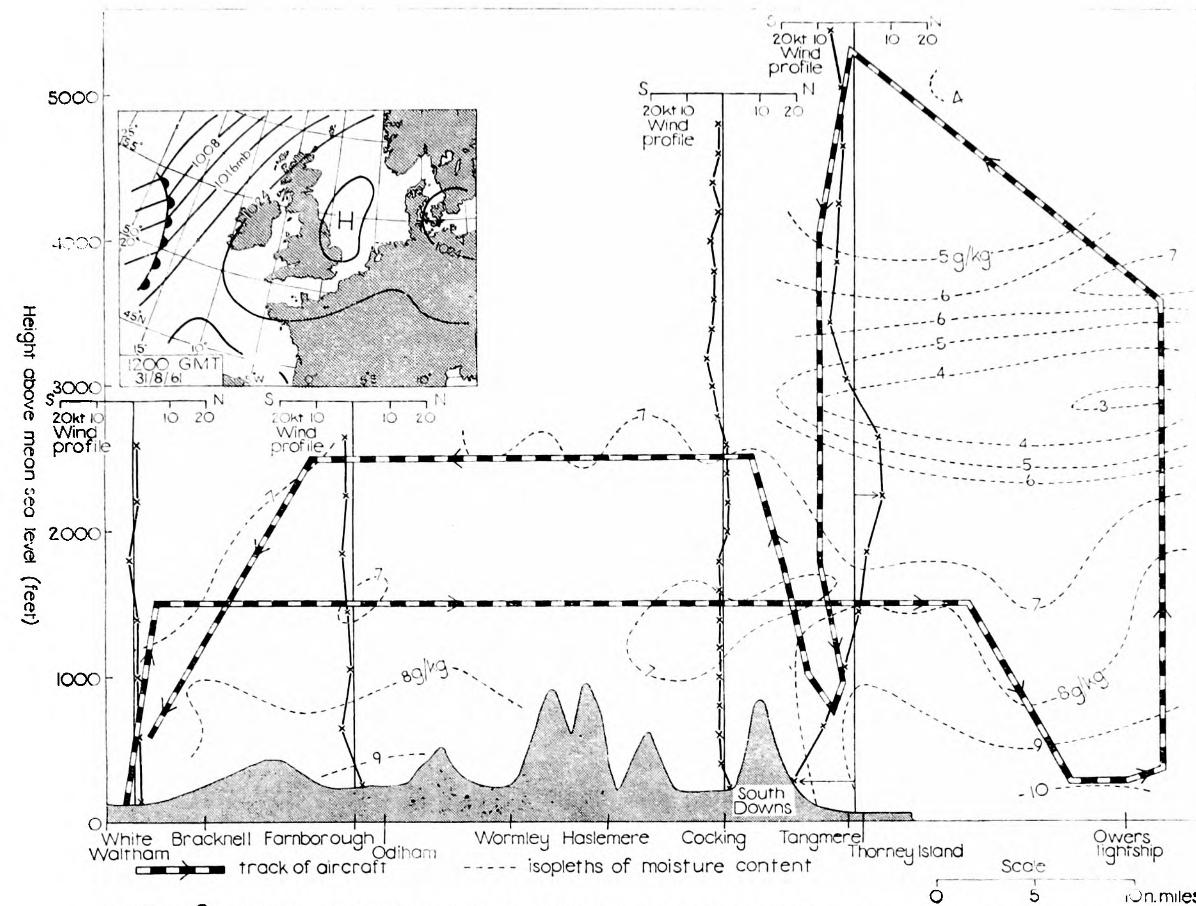

FIGURE 6—WIND PROFILES AND MOISTURE CONTENT ANALYSIS, 31 AUGUST 1961, AT APPROXIMATELY 1430 GMT

Inset shows the synoptic situation at 1200 GMT.

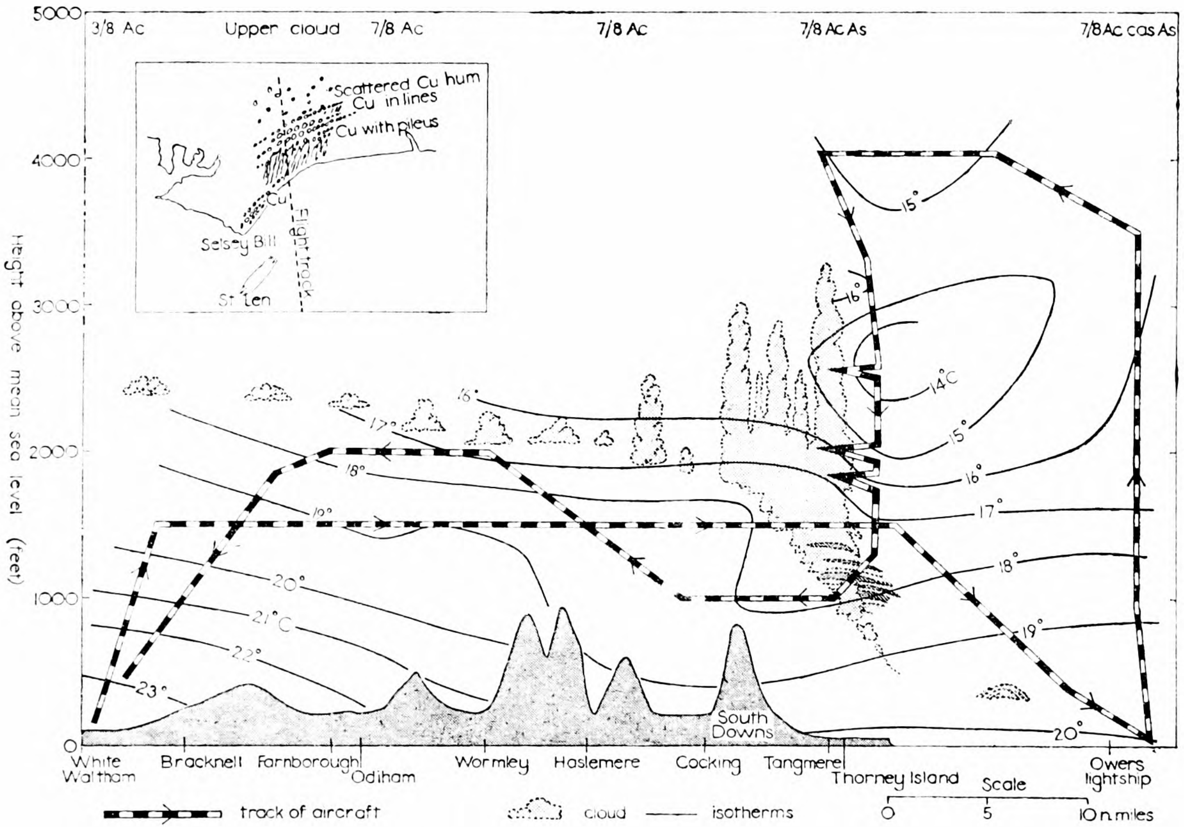

FIGURE 7—ANALYSIS OF DRY-BULB TEMPERATURE, 19 SEPTEMBER 1961, AT APPROXIMATELY 1430 GMT

Inset shows the distribution of cloud at the same time.

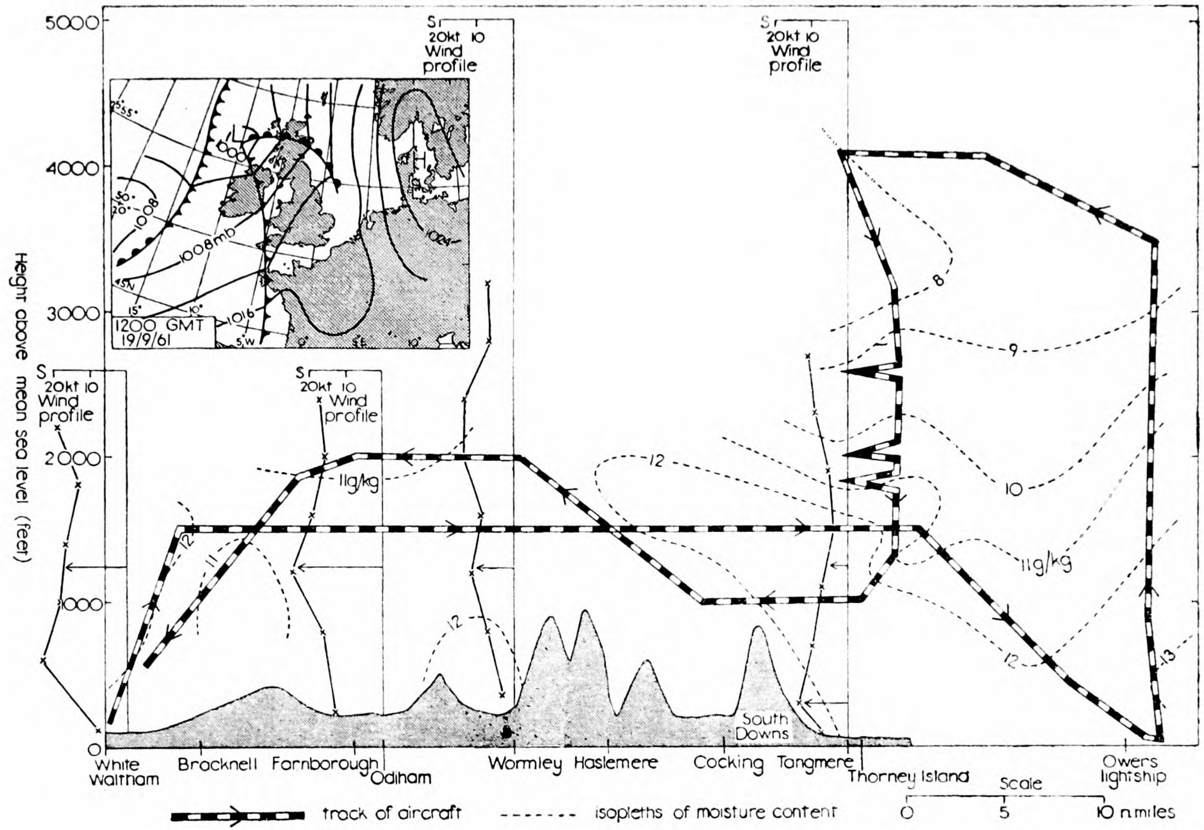

FIGURE 8—WIND PROFILES AND MOISTURE CONTENT ANALYSIS, 19 SEPTEMBER 1961, AT APPROXIMATELY 1430 GMT
Inset shows the synoptic situation at 1200 GMT.

Malkus.[6] Highest tops were at 3300 feet. The temperature pattern showed a region of marked horizontal temperature change in the convergence zone at a height of 2000 feet in association with the presence, or formation, of a cool area at 1500 feet. The most vigorous cumulus clouds were over Tangmere aerodrome and these were probably not due to orographic lifting over the South Downs since the temperature pattern in which they grew could not have been generated by obvious topographical effects.

Another feature of interest was that although the vigorous convergence zone lay over the southern coastal strip, sea air with an almost isothermal lapse rate from 500 to 1500 feet penetrated well to the north of this zone. On the cross-section shown in Figure 7 this stable air had reached the hills around Haslemere. By about 1530 GMT the stable air penetrated to Lasham, some 5 nautical miles south-west of Odiham, and caused the sudden disappearance of good thermal up-currents in which gliders from Lasham were flying.

The cross-section of moisture content shown in Figure 8 shows that the more stable air which penetrated to Haslemere was also more moist and it seems likely that significantly moister sea air, whether or not it was of true sea-breeze origin, had passed through or below the convergence zone marked by the cumulus near Tangmere.

Wind profiles for 1400 GMT are shown in Figure 8. The sounding made at Tangmere reveals an increased on-shore component at low levels which was associated with the backing of the surface wind from 230–240 degrees to 210 degrees for a period of 2 hours. Also the wind component at 1500 feet over Tangmere in the region of cumulus growth is reduced.

Discussion.—The cases of 29 and 31 August 1961, form a useful comparison between a case where a sea-breeze convergence zone did not form and one where it did, both with very stable air above about 1500–2000 feet. The obvious difference is in the wind structure, with no convergence zone forming when the general wind was blowing onshore, but it is probable that if the air had been moist enough to allow condensation in the adiabatically cooled region over the South Downs, the resulting formation of shallow cumulus and the release of latent heat would have accelerated the upward flow of air.

The structure of the sea breeze aloft on 31 August is somewhat surprisingly definite considering the weakness of the surface breeze. The penetration of cool and moist sea air is very well marked up to 1500 feet and, although the breeze itself only moved about 10 miles inland, the patterns of temperature and moisture suggest that the effects of the sea-breeze formation were noticeable 10–12 nautical miles out to sea.

The third case is perhaps the most interesting since there is evidence that moist and stable air was penetrating northwards at low level, although a convergence zone was marked by cloud near the coast.

The cases explored to date are, of course, too few to draw any general conclusions but the analyses of the data gathered reveal a number of interesting features of coastal airflow in relatively stable conditions.

Acknowledgements.—Acknowledgement is made of the ready co-operation and assistance in this investigation of Air Commodore A. G. Dudgeon, C.B.E., D.F.C., F/Lt. Gifford, F/O.'s Patrick and Harris of RAF, White

Waltham; Dr. G. E. R. Deacon, C.B.E., F.R.S. and staff of the National Institute of Oceanography, Wormley; Meteorological Office staff at Tangmere, Thorney Island, Odiham, Farnborough, London Weather Centre and White Waltham.

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551.508.824

AUTOMATIC WEATHER STATION DEVELOPMENT IN THE METEOROLOGICAL OFFICE

By N. E. RIDER

Introduction.—One normally associates the term 'automatic weather station' with a collection of instruments and other equipment which is designed to gather surface meteorological data and to transmit the information from a remote locality where it would be economically unsound to maintain a human observer. Automatic stations are not in any way new to meteorology. The familiar radiosonde is an automatic station, but it must be regarded as of a special type as it is only required to work for a short period although its operational environment is severe. This article will make no reference to upper air observations and will interpret the term 'automatic weather station' in its conventional meaning.

In this country the operational need for automatic stations has to date been only marginal since it has proved generally possible to find people whose normal work requires them to live in the more remote areas and who have been willing to accept the part-time task of observing. However, with the coming of automation to lighthouses and the realization that it might now be possible to fill certain existing gaps in the observing network at permissible cost, interest in automatic weather stations has increased. About two years ago the Instruments Branch of the Office was instructed to undertake a survey of the likely costs of operationally useful systems and to start development on a modest scale. The remainder of this article will give some account of progress to date and of plans for the future.

The development programme.—The aim throughout has been to design and produce a flexible system of automatic weather stations which will provide information of a quality comparable to that which would be expected from a manned station and to do this at a cost which will not be prohibitive to the use of the system. At an early date it was envisaged that the development would proceed in three stages. These stages were not to be distinguished by the quality of the observations to be obtained, but rather by the facilities to be anticipated at the remote observing site. The stage 1 station will require that both land-line facilities and mains power be available at the remote site. At stage 2 mains power will not be used and at stage 3 neither land lines nor mains power will be required. In practice, stages 1 and 2 have largely merged into one as all the meteorological sensors and the transmitting equipment have been designed for low power consumption at low voltage. Radio transmission will only be used in the last stage of development and the length of the radio link will be kept as short as possible. It will probably be used to bridge the gap between the observation point and the nearest convenient telephone line. Wherever possible, land-line connexions are to be preferred to radio links both on the grounds of reliability and cost. This is particularly so when the transmitting and receiving ends can be directly applied to the normal GPO system, that is when both can become normal telephone subscribers.

The present position.—

(*a*) *Meteorological sensors.*—In stages 1 and 2 the telemetering system demands that all parameters to be transmitted be presented in the form of voltages to the voltage/frequency converter which forms the input stage of the telemetering equipment. This is also likely to be so in the stage 3 station. Thus it has been necessary to design what may be regarded as a new generation of meteorological instruments which in themselves could be used together or singly to replace conventional instruments in other applications. Models or design drawings are now available for the sensors for all the conventional parameters with the exception of cloud amount and steps are currently being taken to have a small number of each made. It would be inappropriate here to give a detailed description of each sensor so, as an example, reference will be made to that for sunshine which proved to be one of the most intractable elements to sense in an automatic way. It is well known that the Campbell-Stokes recorder has been adopted as the 'standard' instrument and what was needed was an automatic replacement for this. Plate I is a photograph of the model of the transducer which was developed for this purpose. In effect it is an image discriminator which senses the presence or absence of sharp shadows. A phototransistor is located at the centre of a hemisphere which has alternate opaque and transparent segments. The hemisphere is spun by a small motor so that, in bright sunshine, a series of sharp shadows pass across the phototransistor which in turn provides a train of output pulses. The steepness of the edges of these pulses (the rise-time) is a measure of the sharpness of the shadows and therefore of the directness of the sunshine. A small electronic circuit is used to operate a relay when this pulse rise-time exceeds a certain limit. Adjustments are provided to match the operation of the relay to the definition of bright sunshine provided by the Campbell-Stokes recorder chart. The relay in its turn is used to apply a voltage to an input channel of the telemetering equipment.

(*b*) *The telemetering system.*—This is an audio-frequency transmission system which has been designed to comply with the relevant GPO regulations. A detailed description of its features has been given by Bruley.[1] Here we need only note that it uses a single pair of telephone lines and in its present form is capable of passing information between any two points in the British Isles. It provides 12 information channels and 4 'control' channels and a signal for each meteorological element to be transmitted is passed down one of the information

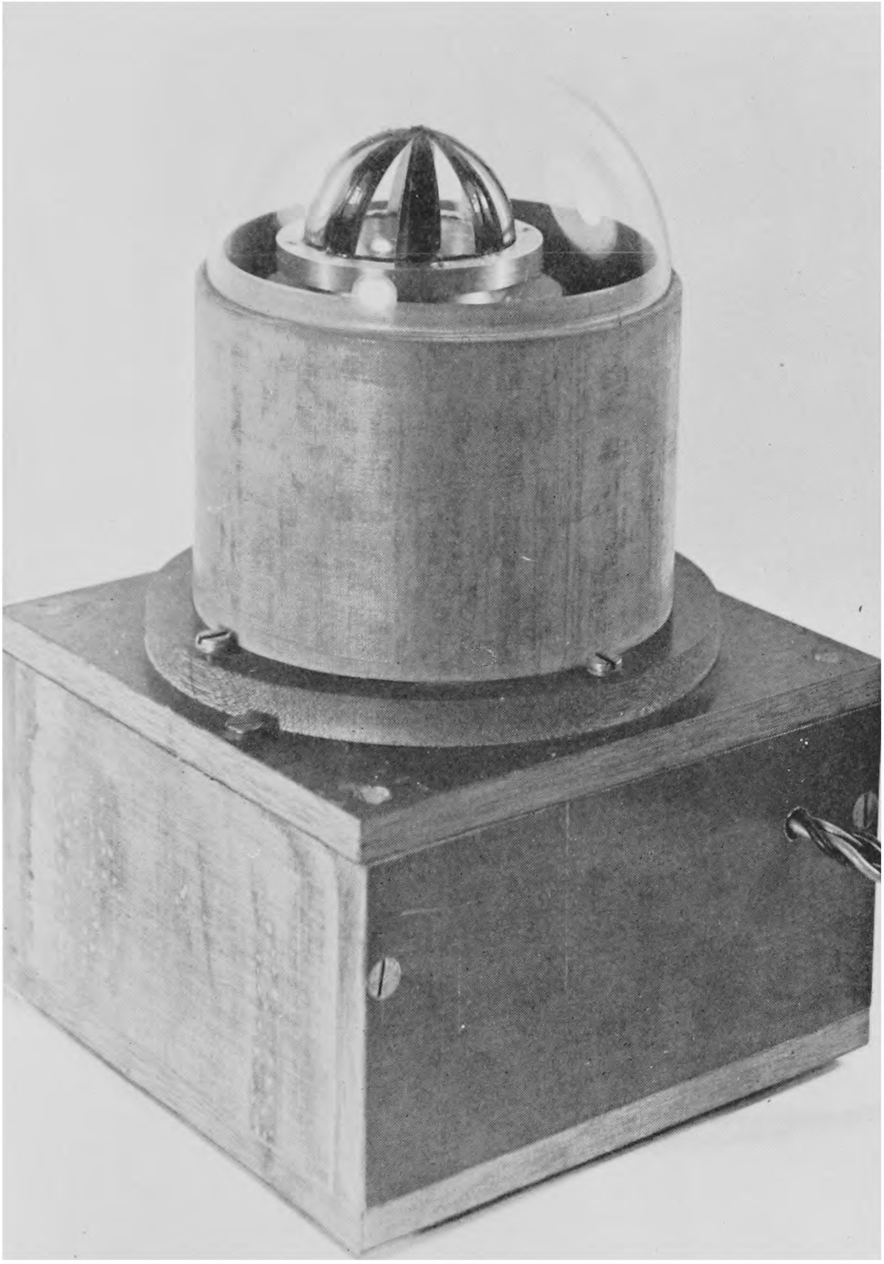


PLATE I—PROTOTYPE SUNSHINE TRANSDUCER TO BE USED AT AN AUTOMATIC WEATHER STATION

(see p. 244)

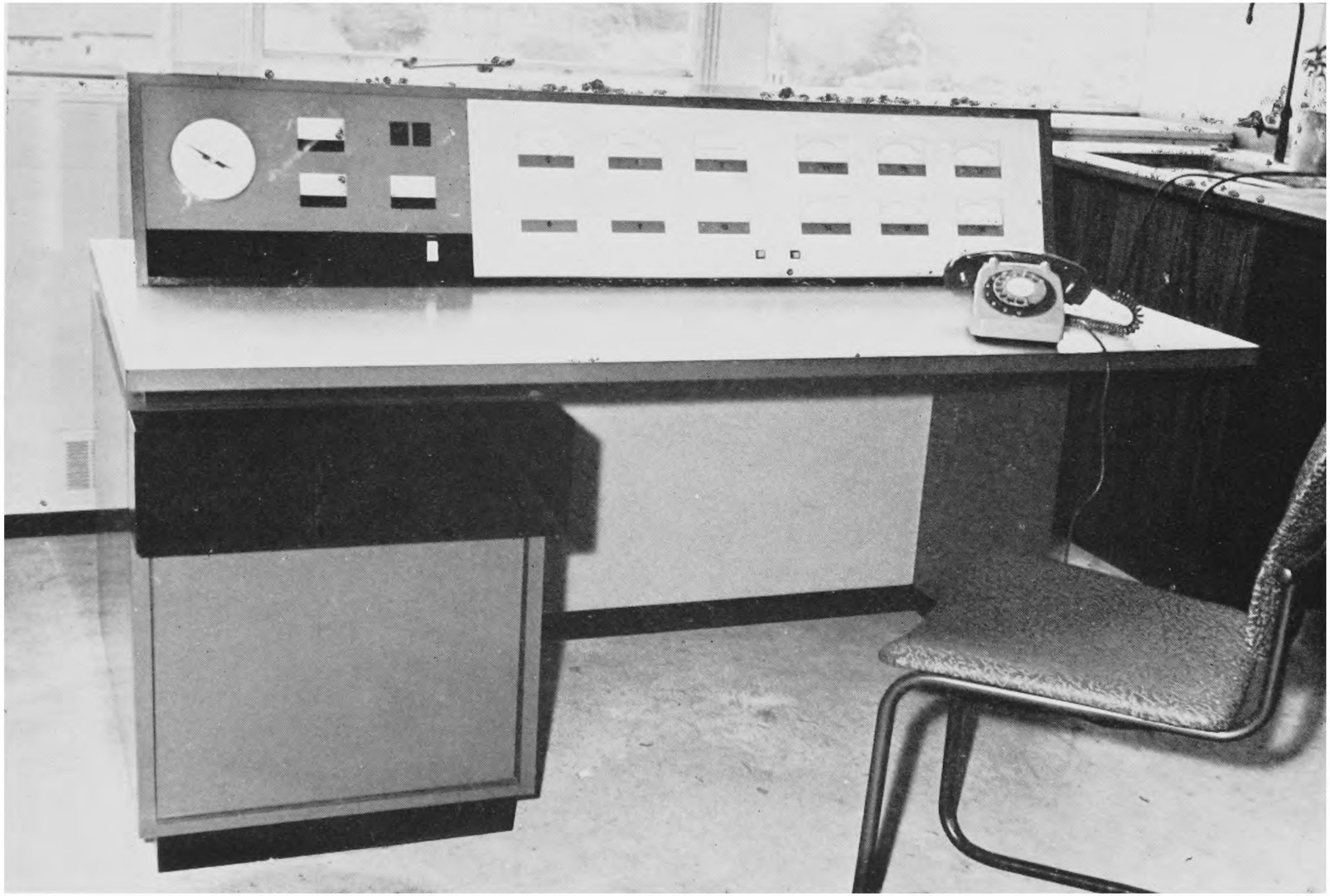
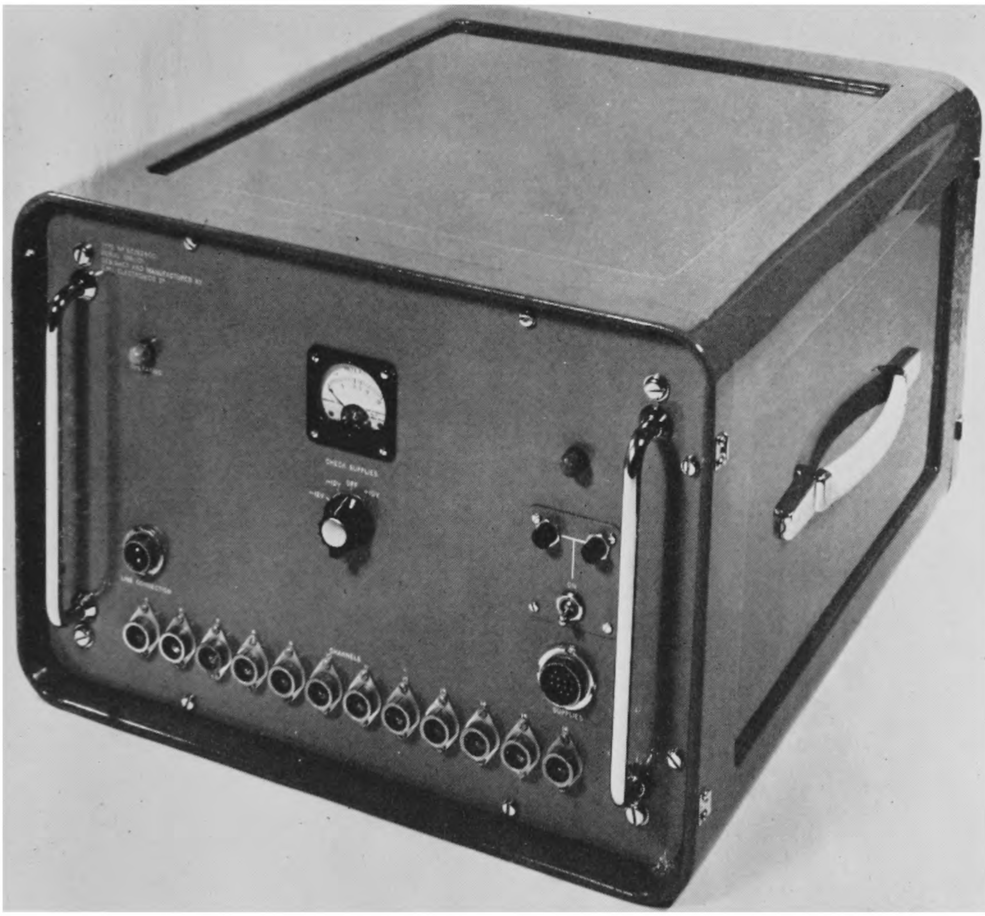


PLATE II—RECEIVING CONSOLE FOR AN AUTOMATIC WEATHER STATION
(see p. 245)



Crown copyright

PLATE III—TRANSMITTER TO BE USED AT AN AUTOMATIC WEATHER STATION
(see p. 245)

To face p. 245

Photograph by G. J. Jefferson

PLATE IV—PHOTOGRAPH OF THE 'SUB-SUN' OVER THE WESTERN NORTH ATLANTIC
(see p. 254)

The photograph was taken at 1420 GMT, 22 March 1963, at 56°N 51°W, from a height of 35,000 feet, looking in the direction of the sun. Extensive frontal cloud, main top estimated at 15,000–18,000 feet, was present. The sub-sun was produced by reflection of the sun's rays by ice crystals in the higher cirrus cloud.

channels, these being automatically cycled in time sequence. Sixteen seconds are needed to cover one complete cycle and the display at the receiver is in the form of deflections on meters calibrated in terms of the meteorological parameters.

The first information channel may be allocated to pressure in which case the meter scale for the standard station would be calibrated in millibars from 950 to 1050 in steps of 1 millibar. The accuracy of the system is such that pressure will be shown correct to the nearest millibar. Plate II shows a prototype of the receiving console, the final version of which will only differ in minor detail, and Plate III shows the transmitter. The 12 display meters of the receiving console may be clearly seen. These cater for pressure, temperature, wet-bulb depression, rainfall (2 meters), rate of rainfall, sunshine, wind speed (10-minute mean), wind direction and visibility. These elements occupy 10 of the available 12 channels and the remaining 2 may be allocated at a later date to such parameters as net radiation, maximum gust in the last hour, etc. It is hoped that the first complete station will be working at Bracknell before the end of 1963. This will be used for assessment purposes following which the development of the stage 3 station will be started.

Method of operation and alternative arrangements.—Basically, the station may be used in two ways, that is, it may be kept in continuous operation or may be interrogated on demand. Continuous operation will require that a private line be provided between the transmitting and receiving points but interrogation will be carried out over the normal public system. To interrogate the station the appropriate number is dialled or requested and once connexion is made a 10-second delay is followed by a tape recording which identifies the station by name or number. This identification is followed by a series of audio-tones which are shown, in terms of the meteorological elements, on the display meters. The transmitter continues to operate for a preset time, normally two minutes, and a series of readings may be taken. The reading on each meter is held for 15 seconds in each cycle and only falls off 1 second before it is replaced in the next cycle. At the end of the preset time the station shuts down automatically and the last cycle of meter readings is held on until the meters are manually reset to zero at any time after the termination of the call. This type of operation is particularly suitable for collecting data at one central point from a number of observing points. Each remote station may be called up in turn, it only being necessary to meet the cost of the calls in the normal way. Thus, one receiver may then be used to interrogate a chain of automatic stations.

The continuous mode of operation is more appropriate to use on large airfields where the central office cannot be conveniently located near the position where it is desired to take the observations. An obvious example is London (Heathrow) Airport where it is necessary at present to maintain a subsidiary office for the express purpose of observing. It would also be possible to bring to a central office observations from various points on the perimeter of any airfield.

It is worth noting that in either mode of operation continuous recording at the remote observing point is possible and that this recording may also be added to the receiver provided that continuous operation over a private line is maintained. Moreover, at extra cost, the meteorological parameters can be presented in digital form at the receiver and print-out and/or punch facilities added.

A further development, primarily intended for airfield use, will enable the operator to dial, using a preset code, for the parameter required at any time. This parameter would then be presented to him in digital form with an indication that the parameter actually demanded was being displayed. Facilities will be incorporated to enable all available parameters to be displayed in turn if this should be demanded.

Conclusion.—Our experience with automatic weather stations in this country is very limited and the operational requirements are ill defined. There is little doubt that there will be an increasing need for the type of facilities now being developed but at this stage it is impossible to forecast the extent or the exact form of use. Both must depend on the quality of the observations that can be provided as well as the reliability and cost of the various alternative systems.

REFERENCE

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551.583.7

PALAEOCLIMATOLOGY

By H. H. LAMB

The beginnings of our knowledge of ancient climates and theories about them go back at least to Robert Hooke, who, in 1686, proceeded from the discoveries of fossil turtles at Portland to the idea that there had been past ages with a much warmer climate in England and that possibly the explanation might lie in shifts of the earth's axis. Active development of work in the field of palaeoclimatology began around 1800–30, with the realization by various observers (John Playfair and the Swiss engineer I. Venetz are the best known) that there had also been at least one great cold epoch in the past when the glaciers were enormously greater in extent than in historical times. Yet palaeoclimatology may rightly be regarded as a new science which is likely to develop significantly in the coming years. New techniques of observation and assessment have, since about 1945, begun to produce a wealth of evidence from many diverse fields of science. This has properly led to the initiation of conferences in several leading countries to bring together the original research workers and interested theorists. Meteorology has been represented as well as geophysics and geology, geomorphology and glaciology, botany, zoology and other disciplines, including sometimes archaeology and history.

The word 'palaeoclimates' (Greek Παλαιος—ancient) means different things to different people. The author has attended two conferences recently under this heading. The first, held in 1962 at Aspen, Colorado under the auspices of the United States National Research Council and National Center for Atmospheric Research, was concerned with the climates of the eleventh and sixteenth centuries A.D., the idea being to test the ability to establish the facts of the past by choosing sample periods not too far back in time. The second conference, sponsored by the North Atlantic Treaty Organization Institute of Advanced Studies, and held in the fine new building of the Department of Physics, Kings College, Newcastle upon Tyne from 7 to 12 January 1963 with Professor S. K. Runcorn as its head, was concerned mainly with the climates of the earth many millions of years ago. The widest range of relevant disciplines was brought together, and a number of applied scientists such as mining engineers were present. Palaeoclimatology is a clear case where knowledge and understanding can only be advanced by interdisciplinary effort. The outcome may soon range from the establishment of a new scientific journal and some organization to maintain regular contacts, to the spreading of beneficial new ideas about where to look (and where not to look) for oil, coal and useful mineral deposits.

When one considers changes of climate over periods of millions of years, there is no doubt that the large-scale geography must be regarded as a variable. There may be interesting lessons for meteorology in this exercise. There is no doubt, for instance, that the land relief has varied and that the positions and arrangement of the main mountain barriers have been quite different in early geological epochs. But when one goes back 200 to 300 million years—a time-span including the Carboniferous, to which the first session at Newcastle was devoted—one encounters phenomena which would be most simply explained if the North Pole at that time lay in the Pacific or near east Asia, with Europe and eastern North America in much lower latitudes than now. Early in the present century Wegener put forward the theory that the continents had also drifted apart and changed their positions relative to the poles during geological time. Within the last ten years these daring theories of pole wandering and continental drift have begun to appear as the simplest (and therefore most plausible) explanation of a mass of heterogeneous evidence, and various geophysical theories have been put forward to account for them. The strongest support comes from measurements of the weak 'fossil magnetism' (remanent magnetization) of rocks serving, as it were, as a very, very weak built-in compass showing the direction and dip of the earth's magnetic field at the time when the rocks were laid down. (The assumption is that, when averaged over any long period of time, the earth's magnetic axis is in line with the axis of rotation, i.e. with the geographical poles. Examination of the observed migration of the north magnetic pole during the last four centuries is enough to lend some support to this idea.) Palaeomagnetic evidence suggests that in the Carboniferous the southern hemisphere continents and India were clustered together around the South Pole. These ideas are in harmony with the apparently tropical character of the vegetation fossilized in most present northern hemisphere coal measures whereas the coals of the southern hemisphere and India appear to show characteristics of a cool temperature vegetation.

The Newcastle meeting was an occasion for sorting out the evidence which fits these constructions and that which still presents difficulties. The warm climate suggested by evidence of flora and fauna over most of the earth in the early Tertiary, 50 or so million years ago, at a time when the North Pole appears to have already arrived near its present position, raises some problems—for instance, the discovery of warmth-loving plants and, recently, of large mammal footprints in Spitsbergen where cold winters with months of darkness must be presumed. At the other end of the time scale, the conference took note of (but refused to grapple with) suggestions of cold climates with glaciers and floating ice over most of the earth in the Pre-Cambrian. Modern techniques of dating make it increasingly possible to treat geological time in numbers rather than as a succession of named epochs, from which the illusion that all geological epochs might be treated as of similar length and presenting *a priori* similar problems can all too easily spring. Since the scattered evidence of glaciation during the Pre-Cambrian may come from times between 500 and 1500 million years ago, it is clearly premature to conclude that we have to develop theories to explain a cold earth in that epoch, i.e. simultaneous cold climates everywhere.

Professor Runcorn himself has been responsible for much of the palaeomagnetic evidence of very ancient climates and very ancient geography, and he is one of its ablest exponents. On this, as on earlier occasions, he appealed to certain directly *climatic* evidence for confirmation of the suggestions about where the poles and continents lay. This climatic evidence is not confined to the traces of former positions of the arid zone (e.g. red sandstones) or of the zones of equatorial and temperate rain-forests. Amongst the sandstones one finds actual fossil sand dunes, from the study of which the ancient wind directions may be deduced. There are puzzles about how a dune becomes fixed and so preserved when desert conditions cease—presumably encroaching subsoil moisture and vegetation play their part—and about why the relatively rarer 'barchan' (transverse) type of dune gets preserved whereas the commoner ones which are set lengthwise in the wind do not. Nevertheless the pattern of wind directions that emerges is quite clear in several important epochs. The Permian sandstones of England and parts of the United States seem to have been laid down in a trade-wind régime. The only surprise is that the north-east to east (palaeo) winds seem to have extended as near the (palaeo) equator (to about 10°N) as deduced by Runcorn. One would have expected some monsoonal disturbance of the wind régime where such big land masses as North America were involved, but the answer may be partly in the probable error of the derived (palaeo) latitudes. In the Triassic desert of South America, in southern Brazil, Dr. J. J. Bigarella of Brazil has found that the fossil sand dunes register an intricate pattern of wind directions remarkably similar to that which prevails at present over the region. (The latitude position in the Triassic should be similar to today's.) He finds the change-over from the northern fringe of the southern hemisphere westerlies to the northerly and north-easterly winds that blow around the cyclonic region over the inner Amazon basin very close to where it is now. Here, then, is an interesting meteorological phenomenon: evidence suggesting a sharpened contrast between the tropical rain-forest and desert in a region where the horizontal arrangement of the atmospheric circulation zones was as it is now. The variables must be sought in other factors—circulation strength (greater persistence of pattern is perhaps unlikely), vertical motion or temperatures and (relative) humidities.

Meteorology can both contribute to, and learn from, these discussions. Moreover, it is vital that any meteorologist who does engage in this field should gain enough acquaintance with the contributions from other disciplines to help him sift fact from fancy. Difficulties abound: the confusions that can arise over attempts to interpret the significance of tree rings are by now well known. This conference heard more of the deposits that can be confused with, and quite wrongly attributed to, glacial drifts (tills) and the difficulties of diagnosis of the origins of soils. There are several approaches that meteorology can use. Professor Sheppard gave the assembly at Newcastle an outline of the present state of our theoretical understanding of the circulation of the atmosphere and of what has been demonstrated by laboratory (simulation) experiments. His opening statement that the problem of climatic variation is the problem of the general circulation of the atmosphere must, however, have seemed to many too bold a claim. It may be largely true for the variations, including ice-ages and interglacials, of the Quaternary, i.e. of the last million years, whilst the geography has remained much as now, and there is a sense in which it must always be true. Even so, it doubtless partly represents the physicist's hope that he has an experiment in which other things remain equal (external conditions constant). The meteorologist's contribution to palaeoclimatology is likely to be along two main roads. Firstly, he must establish both the constant features of the general circulation of the atmosphere and oceans as well as the types and range of variations from short-lived cyclonic and anticyclonic eddies, through changes in the prevailing strength and number of Rossby waves in the upper westerlies up to the scale of climatic fluctuations. This approach was clearly expounded by Professor Sheppard. Secondly, he must go along with the empiricists in other disciplines and identify and map the patterns and sequences of actual climatic changes, both of the recent and the distant past. By gaining a more precise knowledge of the actual nature of some past epochs it may be possible to discover how much of the differences can be attributed to the meanderings of the circulation of atmosphere and oceans and how much evidence there may or may not be of effects due to possible changes of the environment.

551.509.314:551.509.329:551.515.1

FORECASTING THE CENTRAL PRESSURE OF ATLANTIC DEPRESSIONS BY OBJECTIVE METHODS

By J. G. MOORE

Introduction.—The forecasting of visibility at London (Heathrow) Airport 3 and 6 hours ahead during the winter by objective methods has been described by Freeman.[1] The present paper describes the application of similar techniques to the problem of forecasting the central pressure of Atlantic depressions 24 hours ahead. A regression formula has been derived and tested on a year's independent data. The results suggest that the objective methods and the pre-baratics of the Central Forecasting Office (CFO) gave equally good forecasts of central pressures. Both methods are superior to forecasts by persistence.

Data.—Data were extracted for alternate days during 1952–53 for each depression centre found in the area bounded by latitudes 30°N and 70°N and by longitudes 70°W and 5°E, provided the centre was still in the area 24 hours later. Depressions that deepened 20 mb or more on the intermediate days were also recorded. There were 703 depressions in the original sample, but later in the investigation depressions that filled and disappeared while still in the area were included and this brought the number up to 736.

It is important in selecting parameters for use in objective forecasting that they should be physically related to the development of the depressions and they should also be easily obtainable from the synoptic charts in order to make the system operationally practicable. Since the Meteorological Office electronic computer METEOR was used to process the data, it was possible to examine a large number of parameters and retain only the most significant ones.

Parameters extracted from the 500 mb and 300 mb contour charts and from the 1000–500 mb thickness charts included: absolute contour heights at several points relative to the surface centre; the direction, magnitude and components of contour gradients; curvature, vorticity, vorticity advection and a measure of diffluence of the contours; and winds at 300 mb. Another parameter used was the 12-hour change in the 300 mb contour height over the centre. Parameters extracted from the surface chart included: the initial pressure, its change in the previous 3, 6 and 12 hours, the number of closed isobars, the initial latitude and longitude of the centre and the change in the previous 12 hours. The thickness differences 1000–700 mb minus 700–500 mb, and 1000–500 mb minus 500–300 mb, were used as measures of stability.

Preliminary classification of parameters.—Two different methods of objective forecasting using statistical techniques were examined and are described in the next section, but to help determine the most useful parameters each parameter was correlated separately with the central pressure 24 hours later and with the change in central pressure in 24 hours. Using METEOR, a polynomial of the form

$$z = a + bx + cx^2 + dx^3 + \dots$$

was fitted to the data by the 'least squares' method, taking successively higher powers up to the sixth until no further reduction in the root mean square error (standard error) was obtained. The parameters could now be arranged in descending magnitude of correlation with the pressure 24 hours ahead and the 24-hour pressure change.

The highest correlation, 0.72, was between the future pressure and the initial central pressure. It was also noticeable that for the absolute pressure in 24 hours, absolute values of contour height and surface tendencies were high up on the list, whereas for the changes in pressure, wind speed and contour gradients dominated the top ten.

Methods.—

(*i*) *Graphical correlation.*—Freeman[1] described how with a predictand z and two predictors x and y METEOR had been programmed to fit a surface to the data of the form

$$z = ax^5 + bx^4y + cx^3y^2 + \dots + fy^5 + gx^4 + \dots + ux + vy + w$$

by the method of least squares.

The fitting of this surface to the data required the formation of 86 sums of the type Σx^7y^3 (each sum in this case comprising over 700 terms) and the solution of 21 simultaneous equations. METEOR carries out the computations and prints out tables from which prediction graphs could be prepared and the actual graphs of the best fitting relation between z and x and y. It also computes the root mean square error of the predicted values. Then for each of the original observations the predicted value Z_1 was computed from the least squares formula and stored within the machine. These values were then used as the x predictor for another diagram, a new predictor being read into the machine as a y parameter. The process described above was then repeated, and a second least squares formula derived with z as the predictand and Z_1 and the new y parameter as predictors. The predicted value at this second stage, Z_2, was, like Z_1, stored within the machine as a new x predictor and the operation described above was repeated.

This process was repeated until the addition of further parameters produced no significant reduction in the standard error. This usually occurred after about the fifth stage.

(ii) *Multiple non-linear regression.*—Alternatively, with a predictand Z and predictors $x_1, x_2 \ldots\ldots x_{24}$ a regression formula of the form

$$Z = a_0 + a_1x_1 + a_2x_1^2 + \ldots b_1x_2 + b_2x_2^2 \ldots$$

could be fitted to the data by the method of least squares. Up to the 15th power of any of the predictors could be included, but not more than 24 terms could be included in the formula at any time. METEOR had again been programmed to carry out the computations and print the coefficients of the regression formula and the root mean square error of the predicted values.

The most significant difference between the methods of graphical correlation and multiple non-linear regression is that the former method includes terms which are the products of the predictors used whereas the latter method does not. Both the programmes described apply significance tests to the regression coefficients and will discard those that are not significant at the 5 per cent level.

Forecasting the central pressure.—With the large number of predictors involved it was not possible to try all possible combinations of them. It seemed highly probable that the initial central pressure would prove an important predictor and this was adopted as the x predictor at the first stage in the graphical correlation method. The next 20 predictors in the ordered list of correlations with future pressure, plus any of the first 20 predictors in the list of correlations with pressure change not already included, were taken as y predictors, the one that yielded the smallest standard error being selected. At the second and third stages the remaining predictors from the first stage were used again as y predictors and the most successful predictors were selected as before. At the fourth and subsequent stages all the remaining predictors from the two lists with correlation coefficient 0.15 or greater were tried as y predictors.

A similar method of selection was used for the multiple non-linear regression method. The first predictor chosen was, as before, central pressure and each of the next 20 predictors in the first list plus any of the first 20 in the second list not included in these was combined with it in turn, taking all powers up to the sixth which were shown to be significant. Keeping the predictor that gave the lowest standard error, other terms were combined until no further significant reduction in the standard error was obtained.

By this method of selection it seems possible that a parameter which could prove to be a useful predictor when taken in conjunction with another or others might, taken singly, be rejected as unimportant. For instance it seemed not improbable that although the latitude and longitude of the depression centre were individually relatively unimportant as predictors, together they would give a precise specification of position and might prove of greater importance. Various combinations of predictors which were thought to be potentially useful in this way and which had not been included in the earlier selection were tried to see if any further reduction in the standard error could be effected. No significant improvement, however, was obtained.

It was found that the results obtained by multiple non-linear regression were slightly superior to those obtained from graphical correlation and since the former method is simpler to use as a forecasting tool, it was decided to use it in preference to the other. Table I lists the predictors used in the final regression equation and shows their effect as they are introduced successively. The independent correlation coefficients are also shown.

TABLE I—FINAL RESULT OF MULTIPLE NON-LINEAR REGRESSION

	Predictors used	Result of adding successive predictors		Independent correlation
		Residual	Correlation	(magnitude)
1. Central pressure initially	1	9.39	0.72	0.72
2. 300 mb contour gradient (knots) measured over 560 n.miles	1 and 2	8.18	0.80	0.29
3. Change in longitude of centre in previous 12 hours	1 to 3	8.03	0.80	0.25
4. Change in central pressure in previous 12 hours	1 to 4	7.90	0.81	0.45
5. Number of closed isobars within 560 n.miles of centre	1 to 5	7.78	0.82	0.39
6. Month	1 to 6	7.73	0.82	0.41

Standard deviation of central pressure after 24 hours 13.52 mb.

Results and discussion.—Table II was derived from the multiple non-linear regression formula and in conjunction with the instructions for estimating the parameters can be used for forecasting the central pressure. The regression method frequently failed to forecast the change in central pressure of depressions which deepened by 20 mb or more. These 'big deepeners' were therefore studied separately. One can say that for 30 of the 35 cases: (1) the 300 mb wind direction over the centre lay between 190° and 290°, (2) the 300 mb contour gradient was large, (3) the initial central pressure of the low was higher than 980 mb and (4) the month was other than June, July and August, but there were also another 100 depressions which satisfied these conditions but did not deepen markedly. These 130 cases were studied separately but no further predictors emerged as being potentially useful and further investigations did not uncover the essential differences between the 'big deepeners' and the others.

One striking feature of the final regression equation is the small part played by the upper-air parameters as predictors. In fact the 300 mb wind speed over the centre is the only upper-air parameter used at all. It is surprising, also, at first sight, that the corresponding wind direction in conjunction with the speed added nothing useful to the regression formula. The correlations between the change in pressure in 24 hours and both 300 mb wind speed and direction arise mainly from larger falls in pressure being associated with high 300 mb wind speeds and wind directions lying between south and west. As was stated earlier, it was found that in nearly all cases of large falls of pressure both these conditions obtained simultaneously. It seems probable that any contribution made by the 300 mb wind direction is largely implicit in the 300 mb wind speed.

The vorticity measurements, using a grid length of about 280 miles, made in this investigation were disappointing as they contributed no more to the regression equation than did more easily derived parameters. There is a suggestion, however, shown by more detailed computations of vorticity fields at 300 mb over open-wave depressions made by Dixon (not yet published) that a centre of high vorticity advection in the cold air is a typical feature of rapidly deepening depressions. It is possible that more accurate measures of vorticity parameters would have improved the forecasts. Probably a measure of the humidity of the air, and a more accurate index of stability would have led to improved results, had these been feasible.

TABLE II—PREDICTION TABLE FOR CENTRAL PRESSURE AFTER 24 HOURS

†Central pressure	$f1$	Central pressure	$f1$	300 mb gradient wind speed over 560 n.miles	$f2$	Change in longitude of centre in previous 12 hours*	$f3$	Change in central pressure in previous 12 hours	$f4$	Change in central pressure in previous 12 hours	$f4$	Number of closed isobars within 560 n.miles of centre, drawn at 4 mb intervals	$f5$	Month	$f6$
millibars		*millibars*		*knots*		*degrees longitude*		*millibars*		*millibars*					
930	3.4	980	42.5	0	20.0	—10	5.2	—25	0.8	25	29.0	0	0.0	Jan.	1.2
932	5.0	982	44.0	5	20.0	—9	5.5	—24	2.0	24	21.0	1	0.1	Feb.	2.3
934	6.5	984	45.6	10	20.0	—8	5.8	—23	3.4	23	15.1	2	0.5	Mar.	3.3
936	8.1	986	47.2	15	19.9	—7	6.0	—22	4.6	22	11.0	3	1.2	Apr.	4.1
938	9.6	988	48.7	20	19.8	—6	6.3	—21	5.7	21	8.4	4	2.1	May	4.6
940	11.2	990	50.3	25	19.7	—5	6.6	—20	6.7	20	6.8	5	3.2	June	4.7
942	12.8	992	51.8	30	19.4	—4	6.8	—19	7.5	19	6.2	6	4.7	July	4.3
944	14.4	994	53.4	35	19.1	—3	7.1	—18	8.1	18	6.2	7	6.3	Aug.	3.6
946	15.9	996	55.0	40	18.7	—2	7.4	—17	8.5	17	6.7	8	8.2	Sept.	2.7
948	17.5	998	56.5	45	18.3	—1	7.6	—16	8.9	16	7.5			Oct.	1.9
950	19.0	1000	58.1	50	17.7	0	7.9	—15	9.1	15	8.4			Nov.	1.7
952	20.6	1002	59.6	55	17.1	1	8.2	—14	9.2	14	9.5			Dec.	2.7
954	22.2	1004	61.2	60	16.3	2	8.4	—13	9.3	13	10.5				
956	23.7	1006	62.8	65	15.5	3	8.7	—12	9.3	12	11.4				
958	25.3	1008	64.3	70	14.7	4	9.0	—11	9.3	11	12.3				
960	26.9	1010	65.9	75	13.7	5	9.2	—10	9.3	10	12.9				
962	28.4	1012	67.5	80	12.7	6	9.5	—9	9.4	9	13.5				
964	30.0	1014	69.0	85	11.7	7	9.8	—8	9.4	8	13.8				
966	31.5	1016	70.6	90	10.6	8	10.0	—7	9.6	7	14.0				
968	33.1	1018	72.1	95	9.6	9	10.3	—6	9.7	6	14.0				
970	34.7	1020	73.7	100	8.5	10	10.6	—5	10.0	5	13.9				
972	36.2			105	7.5			—4	10.3	4	13.7				
974	37.8			110	6.6			—3	10.7	3	13.3				
976	39.3			115	5.7			—2	11.1	2	12.9				
978	40.9			120	4.9			—1	11.5	1	12.5				
				125	4.3					0	12.0				
				130	3.9										

† To nearest whole millibar.
* Eastward movement positive.

Instructions: Read the values of $f1$, $f2$, $f3$, $f4$, $f5$ and $f6$ corresponding to the observed values of the predictors. The forecast value of the central pressure 24 hours later is given by: $900 + f1 + f2 + f3 + f4 + f5 + f6$ mb.

The objective forecasting technique was tested on independent data for alternate days in 1961. There were 302 cases in this period. Standard errors and correlation coefficients for the objective method, for the routine forecasts of the CFO and for persistence forecasts are shown in Table III. These show that the objective and CFO forecasts are very similar in quality and show that they are both superior to persistence forecasts.

TABLE III—RESULTS OF INDEPENDENT TEST FOR 1961 (302 OBSERVATIONS)

	Root mean square error *millibars*	Correlation coefficient
Objective forecast	7.22	0.84
CFO forecast	7.32	0.83
Persistence forecast	8.94	0.73

Standard deviation of central pressure after 24 hours = 13.13 mb.

REFERENCE

1. FREEMAN, M. H.; A graphical method of objective forecasting derived by statistical techniques. *Quart. J. R. met. Soc., London,* **87**, 1961, p. 393.

551.593.63 (084.1)

A PHOTOGRAPH OF THE SUB-SUN

By G. J. JEFFERSON M.Sc.

The accompanying photograph (see Plate IV) was taken from an aircraft while flying over the western North Atlantic at 35,000 feet and shows what appears to be a mock sun in cirrus cloud below, seen in the same direction as the sun. It was taken on 22 March 1963 at 1420 GMT at 56°N 51°W. The area was covered by heavy cloud masses associated with a depression in the area. The main cloud top can be seen in the photograph and is estimated at 15,000–18,000 feet while variable but often thick cirrus layers extended above this to an estimated height of 25,000 feet.

Minnaert[1] describes this phenomenon as a sub-sun: ". . . seen only from a mountain or an aeroplane. It is a somewhat oblong, uncoloured reflection; the sun reflected not in a surface of water but in a cloud! A cloud of ice-plates, in fact, which appear to float extremely calmly judging from the comparative sharpness of the image". The phenomenon on this occasion was white without any trace of colour fringing. It was also very bright and elliptical in shape with the major axis vertical thus appearing to fit Minnaert's description.

If indeed it is a direct reflection in plate-shaped ice crystals of cirrus cloud floating horizontally then the angle of depression of the 'sub-sun' will equal the angle of elevation of the sun. The following calculation shows that this was so.

The camera was pointed downwards at a suitable angle to include both the sub-sun and the horizon (cloud top), which can be seen near the top of the photograph. This is illustrated in Figure 1. The length of the negative is shown by AB whose mid-point is E. C is the position of the image of the sub-sun and D that of the horizon. Since the lines DG, EL and CH represent rays passing through the optical centre of the lens, F, they can be represented by straight lines. The angle of depression of the sub-sun below the horizon is angle GFH = angle CFD. Measurements on the negative show that CE = 15.5 and DE = 12.5 millimetres. The focal length of the lens EF = 50 millimetres.

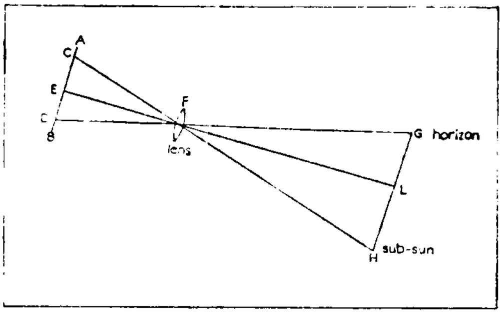

FIGURE I—DIAGRAM SHOWING THE FORMATION OF A PHOTOGRAPHIC IMAGE OF THE SUB-SUN

$$\text{Angle CFD} = \text{angle CFE} + \text{angle EFD}$$
$$= \tan^{-1}\frac{15\cdot5}{50} + \tan^{-1}\frac{12\cdot5}{50}$$
$$= 17^\circ + 14^\circ = 31^\circ.$$

The horizon was a cloud top whose height was not exactly known. Since there was much cirrus present it was probably not more than 10,000 feet below the aircraft. Assuming the horizon to be 2 miles below the level of the aircraft the angle of depression of the horizon is about 2°. The angle of depression of the sub-sun below the horizontal was therefore about 33°.

The time was about an hour before the local noon when the photograph was taken. At noon on this date the sun's elevation at 56°N is 34°, which shows good agreement with the angle of depression of the sub-sun.

REFERENCE

1. MINNAERT, M.; Light and Colour in the open air, (revised edition). London, G. Bell and Sons, Ltd., 1959.

REVIEW

Meteorologisches Taschenbuch Vol. I, (new series, second edition). Edited by Franz Baur. 8½ in. x 5¾ in., pp. vi + 806, *illus.*, Akademische Verlagsgesellschaft, Geest & Portig K.-G., Leipzig, 1962. Price: D.M. 80.

This is a completely remodelled version of the meteorologist's 'Kaye and Laby' started by Linke in 1930. Linke's *Meteorologisches Taschenbuch* as it was called was not, I think, much used in this country. Professor Baur and his collaborators have however gathered together in Volume I of this new edition so much material which synoptic meteorologists (especially those engaged in medium and long range forecasting and research) and climatologists frequently need that I hope it will not suffer the same fate.

Here is a list of the most useful things in it for which little or no knowledge of German is required:

(i) A list of nearly 4000 meteorological reporting stations in order of block numbers with indicator numbers, position, height above mean sea level and types of observation carried out.
(The 13 ocean weather stations, their code letters and position are listed.)

(ii) Pentad values of 500 mb zonal index for 50°–60°N and from 60°W–60°E for the period from 1948 to 1957 in metres per second.

(iii) Mean pressure maps for each pentad of the year for an area 15°W to 30°E and 40°N to 65°N, complied from pentad pressure means 1883–1944.

(iv) Monthly means of surface pressure, temperature and rainfall for nearly 300 stations distributed over the earth. Height above mean sea level and period of the mean are given in each case. The mean number of rain days (with the particular definitions of a rain day in each case) per month are given for about 150 stations.

(v) Monthly temperature anomalies for central Europe (mean of the values for De Bilt, Potsdam, Basle and Vienna) for the period 1761–1960 and the monthly normal for this period.

(vi) Monthly precipitation anomalies for Germany west of the Oder (mean of 14 stations) for the period 1851–1960.

(vii) Monthly pressure anomalies for Basle (1755–1960), Edinburgh (1770–1960), Copenhagen (1842–1960), Oslo (1816–1959), Upernavik (Greenland) (1875–1958), Jakobshavn (Greenland) (1874–1958) and West Greenland (half Upernavik + half Jakobshavn) (1875–1958).

(viii) Monthly values of *Kp* (the international index of magnetic disturbance) from 1932 to 1961 with annual and monthly means.

(ix) Monthly, yearly and overlapping five-monthly values of the sunspot number (Wolf number) from 1749 to 1960.

(x) Monthly and yearly mean values of a solar-flare index from 1882 to 1957.

Should the German titles of some of these tables not be clear there is a very complete glossary of meteorological terms from German to English and to French, Spanish, Italian and Russian. This glossary is not always as accurate as one would wish. For anyone wanting to write up his work in German there is an English index to the glossary so that the equivalent of a term like *vortex filament*, which would not be in an ordinary dictionary, can be readily found.

To this list could be added a daily-type calendar for the period 1881–1960 based on the occurrence or not of rainfall at four stations, Frankfurt on Main, Gütersloh, Hamburg and Potsdam. It enables the distribution of wet and dry spells over an area about the size of England and Wales to be recognized rapidly in a general way. Again, the explanation of the symbols used can be readily obtained from the lexicon.

Over 100 pages are devoted to the World Meteorological Organization (WMO) codes ranging from FM 11A to FM 83A and the details of the individual symbolic elements. This information and the list of reporting stations under (i) above would normally require reference to be made to two WMO publications.

Among items in the book requiring a good knowledge of German are accounts of chart analysis (surface and upper air) and forecasting by Scherhag, and of the treatment of upper air observations by Zimmerschied. Neither contains anything not readily available in English publications, although in

Scherhag's contribution there is a difference of emphasis which is fairly typical of the somewhat different mental approach of English and German meteorologists. With both sections there is a fairly comprehensive bibliography but it is surprising that Sutcliffe's 1938 paper should have been included and not his 1947 one when reference is being made to his development theory.

Finally there is a list of important dates in meteorological history starting with 600 B.C. They are rather few and far between till the sixteenth century, but from then on they become closer and closer, until by 1939 they are so close that one wonders how much thinning-out they will have experienced by A.D. 2000!

There is an interesting list of meteorological journals and magazines with meteorological contributions, arranged in order of year of first appearance. By what, I am sure, is the purest oversight the *Quarterly Journal of the Royal Meteorological Society* does not appear. Perhaps it is because the proceedings of the Meteorological Society appeared under various titles from 1839 before Volume I of the *Quarterly Journal* appeared for 1871–73.

Professor Baur and his collaborators are to be congratulated on providing such a useful book for their meteorological colleagues. They have gathered together in this one volume material which would otherwise have to be sought for in nearly a score of separate publications. I hope meteorologists will make good use of the fruits of this endeavour.

M. K. MILES

OBITUARY

Mr. R. J. Williams, M.B.E.—It is with very deep regret that we heard of the sudden death of Mr. R. J. Williams on 12 May, only a few months after his retirement. A full appreciation of his many years of service in the Meteorological Office appeared in the February, 1963 issue of this magazine.* Our deepest sympathy is extended to his widow in her sad loss.

METEOROLOGICAL OFFICE NEWS

Academic success.—We offer our congratulations to Mr. W. R. Sparks on obtaining a Diploma in Technology, in Applied Mathematics, at Northampton College of Advanced Technology, London.

Brabazon Trophy.—After a period of 13 years the Meteorological Office at London (Heathrow) Airport has regained the Brabazon Trophy for the best departmental aggregate at the Airport sports held on 8 June 1963. In addition to winning a cup for the men's mile relay, Mr. Miller won the 100 yards sprint cup, while Mr. Burn came first in the 220 yards and Mr. Tucker won the high jump. On the ladies' side, Miss Rundle won the long jump, and also shared the trophy for the best field athlete of the day.

CORRIGENDA

Meteorological Magazine Vol. 92, p. 215, on lines five and seven for "ue" read "u_φ"; on line fifteen for "$u\varphi$" read "u_φ".

* Meteorological Office News. *Met. Mag.*, **92.** 1963, p. 68.

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THE JET-STREAM PROFILE AND ITS RELATIONSHIP TO THE THERMAL FIELD

By C. J. BOYDEN

Summary.—Wind speed profiles across jet streams at 300 mb were drawn from observations over the British Isles in winter. The variations of shear on the two sides are given and average values are compared with those found over North America. The position of the jet axis at 300 mb is related to the position of the maximum thermal winds in the 1000–500 mb and 500–300 mb layers. An expression is introduced for the magnitude of the flow across the contours. Forecasting the changes in a jet is regarded as the same problem as forecasting the thickness pattern, and this is discussed briefly.

Introduction.—Study of the jet stream is largely confined to the post-war years but even so the literature on the subject is extensive. A summary of it, together with a comprehensive bibliography, has been published by the World Meteorological Organization.[1] A monograph by Riehl and others[2] in 1954 covered many aspects of the jet stream, and Riehl has recently brought this up to date in a further résumé.[3] Reiter[4] has published what is doubtless the fullest work on jet streams, and his book includes nearly 60 pages of references.

Most of what has been written deals with observations of the jet stream and the analysis of its structure, and less frequently with the role of the jet stream in the mechanism of the atmosphere. The present paper and two others that are to follow are concerned mainly with problems in the day-to-day forecasting of the jet stream. Their aim is the location of the jet stream on an isobaric surface and the forecasting of its subsequent behaviour. Empirical rules are introduced for the more precise application of relationships which are already known, at least in general character.

Most observations used were taken over the British Isles or the nearby Continent and all during the months October to March, so some modification of the results may be necessary in other parts of the world. A two-dimensional approach was adopted using the 300 mb chart because on the average the jet stream is close to that level. In the United States, on the other hand, Endlich, Solot and Thur[5] found the average height of the jet stream to be only a little below the 200 mb level, and because of the greater range of latitude in their observations there was greater variability in this relationship than occurs over the British Isles.

A belt of strong upper winds qualifies for the name 'jet stream' or simply 'jet' when some arbitrarily chosen speed is reached. In this investigation a peak speed of 70 knots at 300 mb has been adopted and categories defined as 'strong' and 'very strong' have been introduced where necessary. In order to distinguish the jet proper from the jet at 300 mb, the line of maximum wind of the former has been referred to as the jet core and the line of maximum wind at 300 mb as the jet axis. For practical purposes the jet axis is regarded as being in the same vertical plane as the jet core.

The height and strength of the jet in relation to the 300 mb pattern.— Nearly 50 jets over the British Isles in the winter of 1961–62 were examined in order to ascertain how satisfactorily their height and strength were represented by the 300 mb contour pattern. The data used were the reported 300 mb height and wind speed together with the height and speed of the maximum wind on the same upper air report. Observations were taken in a zone 200 nautical miles wide centred on the jet axis. On the average the maximum wind speed reported was 10 per cent higher than the 300 mb wind speed, the difference being greater the larger the gap between the jet core and the 300 mb level. Markedly greater differences were found occasionally and these were presumably due to stronger winds very close to the jet core, in a belt so narrow as to be of no great practical importance except in relation to turbulence.

The height of the strongest wind was much more variable than the height of the 300 mb surface and there was no general relationship between these two quantities. For a particular jet, however, there was a systematic difference in the relationship on the two sides of the jet. On the cold side of the jet axis at a distance of 50–100 n.miles the maximum wind occurred at a mean pressure of 300 mb. Within 50 n.miles of the axis the mean height of the maximum wind was 200 metres above the 300 mb level. At 50–100 n.miles distance on the warm side the strongest wind occurred at a mean height of 700 metres above the 300 mb level, although one maximum in three was below it. As many as 25 per cent of all maxima were more than 1 kilometre from the 300 mb surface, but on many of these occasions the wind speed difference between the two levels was not correspondingly large, the vertical profile of wind speed then being rather flat.

The wind speed profile across a jet stream at 300 mb.—

(i) *Jet streams over the British Isles.*—The meso-structure of jets was studied by means of profiles of 300 mb wind speed (see Figure 3) and thermal wind speed over the British Isles during the months October to March in the winters of 1959–60 and 1960–61. This limited area was chosen to ensure uniformity of observational procedure. The observations were restricted to occasions on which a wind of at least 100 knots at 300 mb was reported somewhere, with the further requirement that this speed should be reported at some point on the jet on three consecutive 12-hourly charts. Each cross-section was drawn through Aughton (Liverpool) perpendicular to the strongest observed winds. Soundings within about 200 n.miles of this line were used in constructing the profile unless there was marked confluence or diffluence within this distance, and in transferring observations to the cross-section it was assumed that the intervening contours were streamlines. Slight differences of wind direction were ignored. Large departures from the general 300 mb wind direction were sometimes found in thermal winds, in which case components along the general flow were used. However, such winds were invariably light and were of little consequence in the analysis.

Sixty-two profiles were drawn and it was found that almost all the jets lay in the sector from about south-west through north to north-east, the distribution through the sector being remarkably uniform, though the criteria for selection introduced some bias.

It soon became evident that a profile of 300 mb wind speeds gives the position of a jet axis more precisely than is possible by inspection of the observations or the contours, as well as giving a clearer picture of the distribution of speed across the jet. Some error was introduced because of the use of upstream and downstream observations, but the main uncertainty was in the shape of the profile very close to the jet axis; only occasionally was this defined precisely by observations. Most profiles were considered to be fairly accurate in the zones 50–100 n.miles from the axis.

About one in seven of the profiles showed two jet axes, but to obtain the mean profile about the main axis all were included. This was inevitable since there were also occasions when it was uncertain whether the remnant of a second jet existed.

From measurements at 50 n.mile intervals on either side of 60 jet axes the distribution of mean 300 mb wind speed was found to be as in Table I.

TABLE I—MEAN 300 MB WIND SPEED ON THE JET AXIS AND AT VARIOUS DISTANCES ON EITHER SIDE

	Warm side			Jet axis	Cold side		
Distance from axis (n.miles)	150	100	50		50	100	150
300 mb speed (mean for 60 jets) (knots)	90	100	116	130	115	92	73

It will be noted that the innermost 100 n.miles of the jet showed an almost symmetrical profile. This arose partly from the subjective drawing of the profile, but since the shape depended on observations both inside and outside the zone this is not thought to have affected the mean profile appreciably except perhaps in the estimate of the speed on the axis. In the zones 50–100 n.miles from the axis the mean shear was 44 per cent greater on the cold side than on the warm side. This difference was still greater at 100–150 n.miles from the axis, partly because of a tendency for a minor jet axis to lie on the warm side. It is of interest, however, that as many as one in three of the jets showed the greater shear on the warm side.

An attempt was made to relate the profile to acceleration and deceleration of the air in the jet, but this was abandoned because of the difficulty of finding enough occasions when the changes in speed following the motion were beyond question. An alternative approach was made by classifying the jets as 'strong', when the peak speed on the profile was between 100 and 129 knots, or 'very strong', when it was 130 knots or more. Of the very strong jets, the occasions of acceleration over the past few hours must have exceeded those of deceleration for the reason that when a variable is close to its extreme level the chances of there having been a higher value some hours earlier are small. This distribution of mean 300 mb wind speed in strong jets and very strong jets is given in Table II.

TABLE II—MEAN 300 MB WIND SPEEDS ON THE JET AXIS AND AT VARIOUS DISTANCES ON EITHER SIDE FOR STRONG AND VERY STRONG JETS SEPARATELY.

	Warm side			Jet axis	Cold side		
Distance from axis (n.miles)	150	100	50		50	100	150
300 mb speed (mean for 34 strong jets) (knots)	80	89	103	116	104	87	73
300 mb speed (mean for 26 very strong jets) (knots)	105	115	132	148	128	99	73
Difference (knots)	25	26	29	32	24	12	0

This table shows that the mean profile of strong jets was highly symmetrical and hence that the asymmetry noted in Table I at distances greater than 50 n.miles from the axis arose wholly from the skew distribution of mean speeds in very strong jets. In these the mean cyclonic shear was nearly double the mean anticyclonic shear. It is of interest that the speed at 150 n.miles distance on the cold side is the same in the two classes.

Figure 1 shows the relationship between the 300 mb wind speed on the jet axis and the cyclonic shear between 50 and 100 n.miles away. The mean curve shows a large increase in shear with jet speed, although the scatter is quite large. The broken line indicates a shear equal to the Coriolis parameter ($f =$ 21 knots/50 n.miles in latitude 55°). The proportion of shears of at least this magnitude increases from 23 per cent for strong jets to 77 per cent for very strong jets. Five of the 60 jets showed a shear greater than $2f$.

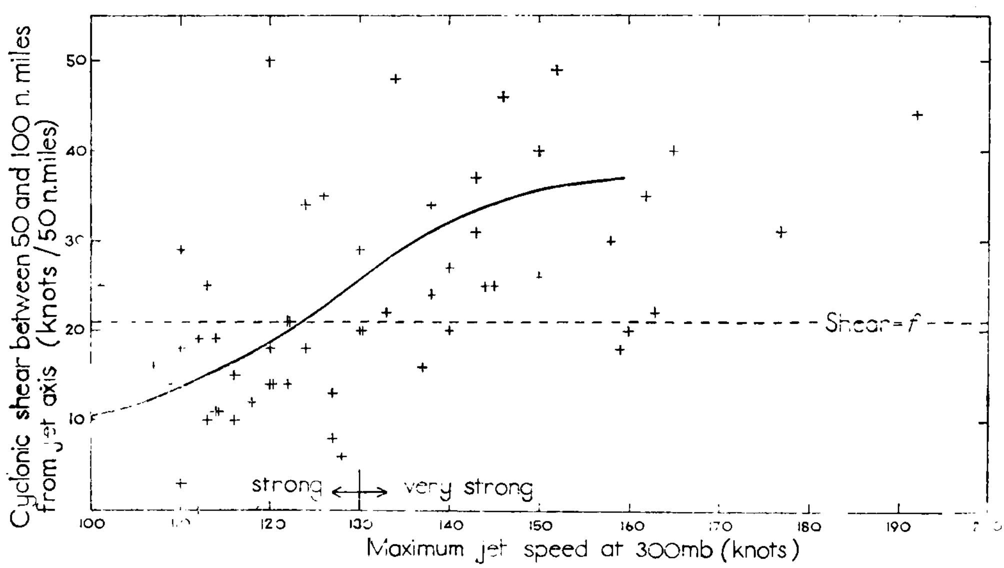

FIGURE 1—SHEAR ON THE CYCLONIC SIDE OF JETS

———— mean curve

Figure 2 is the corresponding diagram for anticyclonic shear at the same distance from the jet axis. Here the shear is limited by inertial instability and the mean curve remains below the 'f' line at all speeds. Nevertheless, 14 per cent of the strong jets and 31 per cent of the very strong jets had an anticyclonic shear at least equal to the Coriolis parameter. These figures suggest that inertial instability occurs at 300 mb on most very strong jets at some point along their length, though the uncertainties in an individual profile

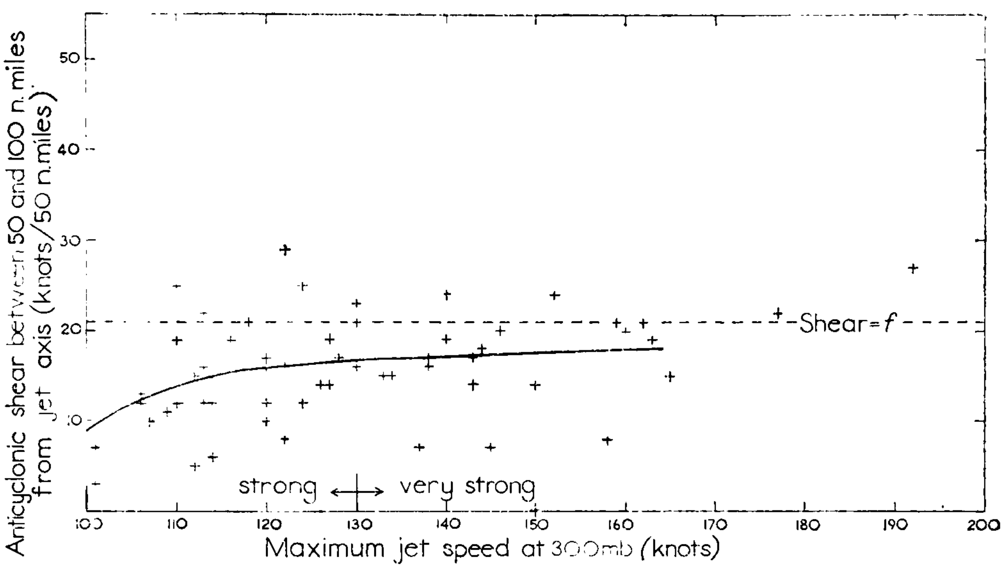

FIGURE 2—SHEAR ON THE ANTICYCLONIC SIDE OF JETS
———— mean curve

should not be overlooked. Crossley[6] quotes a number of reported anticyclonic shears exceeding the Coriolis parameter, but regards the evidence for them as inconclusive.

(ii) *Comparison with results obtained over North America.*—A comparison was made between the wind speed profiles and those published by Endlich and McLean[7] and Reiter.[8] The first of these papers gives profiles constructed from observations by aircraft of Project Jet Stream during a variety of traverses extending from above the jet stream to 2 or 3 kilometres below it. Each profile was defined in terms of the percentage speed reduction at intervals of ½° latitude from the jet axis. The diagram in the paper was used to estimate mean percentages at 50, 100 and 150 n.miles from the jet axis. Rows *A* and *B* of Table III show how these figures compare with the corresponding figures for the profiles used in preparing Table I. The main difference is that the Endlich and McLean profile is the shallower of the two. The same difference appears between rows *D* and *E*, which were based on jets with peak speeds of 130 knots or more, and it seems likely that the differences are real rather than the outcome of different methods of observation. As the authors point out, the American jet streams were studied over the south-eastern United States, so there are large latitude differences between the two sets of observations. Moreover, the aircraft measurements were limited to occasions when the ground was visible.

TABLE III—MEAN OF PERCENTAGES OF PEAK SPEED AT VARIOUS DISTANCES ON EITHER SIDE OF THE JET AXIS OR CORE.

Row	Source	Range of speeds	Distance on warm side in n.miles			Jet axis	Distance on cold side in n.miles		
			150	100	50		50	100	150
		knots	*mean percentage of peak speed*						
A	Boyden	≧ 100	70	77	89	100	89	72	57
B	Endlich and McLean	63–187	78	83	91	100	84	74	70
C	Reiter	?	70	79	89	100	82	67	55
D	Boyden	≧ 130	71	78	89	100	87	67	49
E	Endlich and McLean	≧ 130	75	82	90	100	82	71	61

The profile found for jet streams over the British Isles are very similar to those published by Reiter[8] for jet streams over the United States and southern Canada (and therefore mostly north of the area covered by Project Jet Stream). From radar-wind reports of maximum wind over a band extending 400 n.miles on either side of the jet Reiter derived regression equations for the wind speed profile on either side. Row *C* of Table III is composed of percentages given by these equations. Comparison with row *A* shows almost perfect agreement on the anticyclonic side of the jet and good agreement in the large mean shear over 150 n.miles on the cyclonic side.

The estimation of cross-contour flow.—The acceleration of a parcel of air moving horizontally is derived from the work done by the pressure gradient as the air passes through isobaric surfaces. If V is the wind speed, z the height of the isobaric surface, g the acceleration due to gravity, ρ the air density and n is the horizontal displacement of the air down the gradient, this relationship between work and kinetic energy is

$$\int_{n_1}^{n_2} g\rho \frac{\partial z}{\partial n}\,\mathrm{d}n = \tfrac{1}{2}\left(\rho_2 V_2^2 - \rho_1 V_1^2\right), \qquad \ldots (1)$$

suffixes 1 and 2 referring to the initial and final states.

It will be assumed that ρ remains constant (as it would on an isobaric surface), that there is geostrophic balance in the initial and final states and that $\mathrm{d}z/\mathrm{d}n$ changes at a uniform rate. Equation (1) then becomes

$$g\left[\left(\frac{\partial z}{\partial n}\right)_1 + \left(\frac{\partial z}{\partial n}\right)_2\right]\delta n = \left(V_2^2 - V_1^2\right).$$

Introducing the geostrophic relationship this becomes

$$f\,(V_1 + V_2)\,\delta n = V_2^2 - V_1^2,$$

$$\text{therefore } \delta n = \frac{V_2 - V_1}{f}. \qquad \ldots (2)$$

Thus, with the assumptions made, the distance moved across the contours (relative to the ground, not to the contours) is proportional to the change of wind speed and does not depend on its absolute value at any stage. If V is in knots and δn in nautical miles then $\delta n = 2.3\,(V_2 - V_1)$ in latitude 55° and $\delta n = 2.7\,(V_2 - V_1)$ in latitude 45°.

In passing it may be mentioned that equation (2), which can be written $\mathrm{d}V/\mathrm{d}n = f$, implies that if air moves horizontally across contours to higher pressures it will continue to do so for as long as its speed as given by this equation exceeds the geostrophic speed. Thus an anticyclonic shear equal to the Coriolis parameter is the criterion for inertial instability.

The angle of cross-contour flow is $\tan^{-1}\,(1/f)(\mathrm{d}V/\mathrm{d}s)$ where s is measured along a streamline. Air moves towards lower contours on accelerating to jet speeds, and towards higher contours on deceleration at the jet exit. This effect is sometimes especially noticeable where the air from a jet enters a diffluent ridge. In general, therefore, a jet is more anticyclonic in shape than the corresponding contours, and its axis is determined better from wind profiles than from contours, however accurately these may be drawn. Since 500–300 mb thickness lines move roughly with the 300 mb flow there is a tendency for them to become aligned along the flow, and differences between the thickness pattern and the contour pattern often reflect the ageostrophic component of flow. Thus thickness lines along a jet also tend to be more anticyclonic than the 300 mb contours. Again, the thickness lines at the base of a sharp thickness trough are often more bulbous than the trough itself through outflow resulting from the excess speed of the air. Dynamical temperature changes are of course also involved in both cases.

The use of thermal fields as an aid to forecasting the 300 mb jet streams.—

(i) *Associations between the* 300 *mb jet stream and thermal profiles.*—In principle the problem of forecasting the movement and development of a jet is best tackled by means of observations at the jet level. On the other hand the coherence of the atmospheric mechanism is an encouragement to use associations with lower levels, where moreover the flow patterns are known in some detail and can be forecast with fair success.

The height of the 300 mb surface is highly correlated with the mean temperature of the underlying atmosphere. Advection of warm air must be accompanied by a rise of 300 mb height unless there is compensating divergence, and such divergence rarely outweighs the advective thickness change unless the latter is very small. In the same way advection of cold air usually causes a fall of 300 mb height. In order to obtain a more specific relationship, changes of 300 mb height over Crawley in a 12-hour period were compared with the corresponding changes in 500–300 mb and 1000–500 mb thicknesses. For the 500–300 mb layer it was found that a thickness change of 4 decametres or more was almost always accompanied by a 300 mb height change of the same sign. Moreover the height change was approximately double the thickness change, as might be expected since the layer involved constitutes nearly half the atmosphere below 300 mb. For the 1000–500 mb layer the relationship was somewhat similar but not as uniform. The probable explanation is that thickness changes are greatest where thickness lines are crowded, and for the 1000–500 mb layer it is here that cyclogenesis takes place most frequently; consequently the thickness change is not dominated by advection to the same degree as in the 500–300 mb layer.

It follows that since a jet stream coincides with a concentration of 300 mb contours it is related, both in position and strength, to a concentration of 500–300 mb or 1000–500 mb thickness lines. In synoptic analysis, as distinct from forecasting, the relationship between the jet and the 500–300 mb thickness pattern has little application because if the thickness pattern is known so also is the 300 mb pattern. On the other hand the 500–300 mb thickness pattern has its use in forecasting jet changes since its evolution can often be foreseen without undue difficulty. Nevertheless the 1000–500 mb thickness field was found to be the more generally useful of the two, bearing in mind that any low-level pattern is known more precisely and can usually be forecast more successfully than a high-level one.

For most of the 60 jets it was possible to construct profiles of 300 mb wind speed and 1000–500 mb wind speed up to a distance of 150 n.miles on each side of the respective maximum. In general a peak in the thermal wind profile was associated with a peak in the wind at 300 mb but was displaced horizontally from it. The maximum wind at 300 mb was found to be roughly twice the maximum 1000–500 mb thermal wind speed, and a forecast from this relationship would have given the speed on the jet axis to within 25 knots on three occasions out of four.

Figure 3 shows the two mean profiles, the speeds being given as percentages of the maximum on each curve. It will be seen that the mean position of the maximum 1000–500 mb thermal wind was on the warm side of the jet axis and nearly 60 n.miles from it. The separation between the two was less than 100 n.miles for 70 per cent of the jets. The position of the 500–300 mb peak wind was less easy to locate on many occasions but tended to be about 40 n.miles from the jet axis on its cold side.

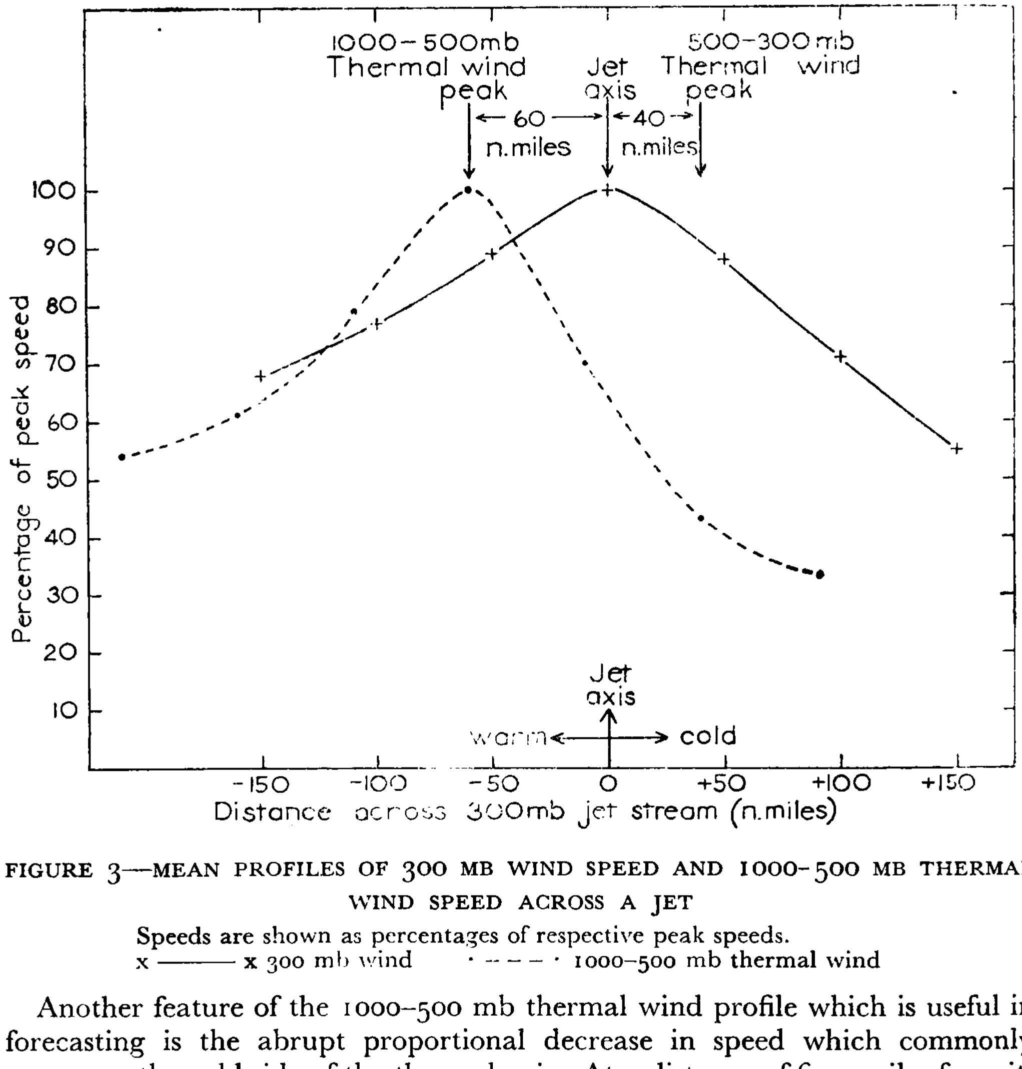

FIGURE 3—MEAN PROFILES OF 300 MB WIND SPEED AND 1000–500 MB THERMAL WIND SPEED ACROSS A JET

Speeds are shown as percentages of respective peak speeds.
x ——— x 300 mb wind · – – – · 1000–500 mb thermal wind

Another feature of the 1000–500 mb thermal wind profile which is useful in forecasting is the abrupt proportional decrease in speed which commonly occurs on the cold side of the thermal axis. At a distance of 60 n.miles from it, below where the jet axis is likely to be found, there is a reduction of 35–40 per cent in the thermal wind speed, an average decrease of about 25 knots.

Thus the 1000–500 mb thermal wind not only provides strong supporting evidence for the position of a jet axis but may be the only basis for locating it if the jet profile is rather flat. There are also occasions at isolated upper air stations when the decrease of the 1000–500 mb thermal wind is the only evidence that the jet has arrived. For if the jet is of cold-front type the thermal wind speed peak precedes the jet axis by about 60 n.miles, so not only is a decrease of thermal wind speed significant but it is a feature more easily recognizable than the eventual decrease of 300 mb wind on the cold side of the jet axis.

(ii) *The advection of thickness lines.*—The accuracy with which the lateral movement of a jet can be forecast is somewhat less than the accuracy of forecasting the movement of thickness lines since the jet remains tied to the line of strongest thermal wind, not to a particular thickness line. The difficulty of forecasting the thermal profile by subjective methods can be demonstrated by considering simply the non-advective movement of thickness lines which results from vertical motion.

The temperature change resulting from movement through an isobaric surface is given by

$$\frac{\partial T}{\partial t} = -w\ (\Gamma - \gamma),$$

where T is the temperature, t the time, w the upward velocity relative to the surface, Γ the adiabatic lapse rate (for dry or cloudy air as appropriate) and γ the actual lapse rate.

In consequence of vertical motion an isotherm (or thickness line) is moved in a direction s with a velocity

$$\frac{w\ (\Gamma - \gamma)}{\partial T/\partial s}\ .$$

If s is taken along a streamline and V is the wind speed, the thickness line moves with a speed V' given by

$$V' = V\left[1 + \frac{w\ (\Gamma - \gamma)}{V\ (\partial T/\partial s)}\right]$$

It is not easy to deduce how the second term on the right-hand side, representing the proportionate departure from wind speed of the movement of the thickness lines, varies with height. The 1000–500 mb layer and the 500–300 mb layer are roughly separated by the level of non-divergence so, with the usual assumption of little vertical motion near the tropopause, there should be no great difference in mean vertical velocity between the two layers. However the term $(\Gamma - \gamma)$ should be greater at lower levels because the mean value of γ is smaller. Hence the numerator should usually be greater at lower levels. The denominator, on the other hand, is the product of two terms of which V is observed to increase with height and the magnitude of $\partial T/\partial s$ to decrease. Thus the movement of the thickness lines in relation to the wind in the two layers cannot be compared from general reasoning.

In view of these uncertainties an attempt was made, by drawing 300 mb trajectories, to measure the non-advective component of 500–300 mb thickness change. This proved impossible with winds stronger than about 60 knots, primarily because thickness lines were then close to contours, so a small error in the direction of the estimated trajectory introduced considerable uncertainty in the thickness change undergone by the air. In addition strong winds often involve large ageostrophic flow and the contours are not then representative of the streamlines. It was therefore necessary to select situations of moderate or light 300 mb flow in which the thickness lines were more nearly across the flow than along it. Pairs of points A and B were chosen such that in 12 hours the air at 300 mb would travel from A to B with a mean velocity V. A further requirement was that A and B should be near radiosonde stations and that the thickness gradient along AB should be fairly uniform. If z_1 and z_2 were the initial 500–300 mb thicknesses at A and B respectively, the advective thickness increase at B would be $12V(z_1 - z_2)/AB$. If the thickness lines in fact had a mean velocity V' along the trajectory, the thickness increase at B would be $12V'(z_1 - z_2)/AB$. Thus V'/V is obtainable from a pair of consecutive 300 mb charts.

From a total of 25 trajectories, 35 knots being the mean 300 mb wind speed, the mean speed of the 500–300 mb thickness lines was found to be 20 knots, a reduction to 55–60 per cent of the 300 mb wind speed. As far as could be judged the thickness lines moved further than the air on two occasions and in the opposite direction on two others. Thus the sign of the reported thickness change was the same as that of the advective thickness change on 23 of the 25 occasions.

The assumption that the 500–300 mb thickness lines move at rather more than half the 300 mb wind speed is perhaps the best guide in the absence of detailed computations. Nevertheless the rule is not easy to apply in regions of strong winds because ageostrophic components are often large; in consequence the advecting wind may differ significantly in direction from the 300 mb contours. As an example of this it is not uncommon to observe thickness lines lying nearly stationary across parts of a jet stream. This implies coincidence with the 300 mb flow which, as mentioned earlier, is usually more anticyclonic than the contour pattern.

Much the same reduction in speed is commonly applied in forecasting the movement of the 1000–500 mb thickness lines, though in this layer a more variable relationship is to be expected. In particular there are non-adiabatic changes which are of greater relative importance in a layer which rests on the earth's surface and is therefore affected by vertical transfer of heat and moisture. In forecasting the movement of thickness lines such complicating factors are allowed for with fair success and in addition consistency between the thermal pattern and the frontal pattern is a valuable aid in estimating thickness advection.

The general assumption that the thickness lines for any layer move on the average at rather more than half the wind speed in the layer is supported by the fact that an isobaric system moves at roughly the same speed at all levels in the troposphere. When allowance is made for the other factors mentioned above this assumption provides an adequate basis for estimating how a jet stream will move, whether it will back or veer, and whether it will strengthen or weaken.

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551.524.34:551.583.14

THE WEATHER: PAST AND FUTURE

By H. H. LAMB

Last winter was the coldest in the English lowlands since 1740—that is to say for 223 years. With the ground under snow in many places for about 60 days, it was possibly the snowiest for 150 years. The closest parallel on most counts seems to have been with the winter of 1795. The average temperature for the three winter months was about freezing-point and by February sea temperatures between the Thames and Holland had been reduced to about this level also. Looking at it another way, conditions in the south of England last December, January and February were about what you would expect during an average winter in south-west Sweden, northern Poland, and the eastern marches of Germany beyond Berlin.

Does this mean we can say: 'No need to do anything about it. We won't see the like again'? I believe such a conclusion may be dangerous. One does not want, either personally or nationally, to embark upon excessively costly preparations to meet conditions that may only occur once in two centuries. But neither do we want to expose ourselves to needless losses on vulnerable crops and garden plants or to unnecessary discomfort if harsh frosts should prove more common. All sorts of things are involved, from fashions in clothing to house design, especially plumbing, and from fuel and power supplies to road versus rail transport and keeping roads clear.

This winter I envied an elderly gentleman I know who has a garden snow-plough, just a curved blade attached to handles like those of a lawn-mower and mounted on a skid. For all his years he cleared his paths and his drive far more easily than I did. Yet this bygone mail-order article seems to be no longer on the market. One wonders, is there room for enterprise in the development of gadgets like this, or setting up lampposts in the middle of riverside flood meadows for skating, as our grandfathers did? The more one looks into the variations of our climate the more it appears that there may be a case for doing some things not done in the recent past.

The first thing we should notice is that the early part of this century (or more precisely 1896 to 1937) was a period of exceptional immunity from difficult winter conditions: and this was just when most of those now in positions of management grew up. It still bulks large in most people's impressions of what is normal. Unfortunately, nearly all modern tables of climate statistics are based all too largely on this fairly recent period, and so serve to reinforce our false impressions of 'normality'. On a reasonable definition of what constitutes a cold winter there were only 2 during those 42 years. But there have been 7 since. In the same period there never was a month in central England with average temperatures below the freezing-point. Again, this has occurred once or twice in each decade since, a frequency that was normal in the nineteenth century.

Another respect in which the last 25 years (that is, since 1937) have established a return to the winter climate of, say, the 1880's or '90's is in the frequency of snow-covered ground (in the country, not in our artificially heated cities). Winters with 15 days or more of snow cover, that is at least half a month all told, were 1 in 7 both at Cambridge and in the Shetland Isles between the wars; since 1938 they have risen to 1 in 3 at Cambridge and 4 out of 5 of all winters in the Shetlands. All our lowland districts show corresponding increases.

What does this mean? The early part of this century appears to have seen the culmination of a 200-year period of gradual warming of the climates in most parts of the world, especially in the Arctic. Our summers, as well as our winters, were affected and the other seasons too. Naturally, it was an uncommonly favourable time for growing delicate plants and crops in the open, and a time when many easy-going (possibly artless) habits grew up. We may have to go back to before the year 1300 to find a half-century of equal warmth (Figure 1).

FIGURE 1—GATHERING GRAPES, PROBABLY IN AN ENGLISH MEDIEVAL VINEYARD*

Between the wars the area of 'permanent' pack ice on the Arctic Ocean diminished by 10 to 20 per cent. In the late summer of 1938 there was so much open water all along the north coast of Asia that prospects for the Russians' northern sea route, the long sought after North-East Passage to the Orient, looked bright indeed. There were scientists who thought that there might be no part of the ocean permanently ice covered by the end of the century. But the changes we have seen since then show clearly that such bare extrapolation is not enough. We need a broader and deeper understanding of what is going on.

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* From the calendar section of the Peterborough Psalter, executed about the middle of the thirteenth century, this picture is close to William of Malmesbury's description (*c.*1150) of Thorney, only 6 miles north-east of Peterborough—"so fully cultivated that no portion of the soil is left unoccupied. On the one hand, it may be seen thickly studded with apple trees; on the other, covered with *vines*, which either trail along the ground, or are *trained on high supported on poles*".

To face p. 270

Reproduced by courtesy of Planet News

PLATE I—A SWEDISH ICEBREAKER CLEARING A PASSAGE FOR TWO FISHING VESSELS THROUGH THE FROZEN SEA OFF MALMÖ IN FEBRUARY 1963

(See page 271.)

To face p. 271

Reproduced by courtesy of the Mansell Collection

PLATE II—'HUNTERS IN THE SNOW' (1565), BY PIETER BRUEGHEL THE ELDER

(See page 271.)

The breadth of open water in the Arctic attained in September 1938 has apparently never been repeated. By the mid 1950's occasional severer years led people in Iceland to think that the epoch of warming had been succeeded by what they called one of 'unstable equilibrium'. But since the beginning of 1958 the Arctic has been colder almost all the time except for a few months in 1959, and the ice has been plainly increasing. The shipping season in Spitsbergen, which had lengthened from an average of three months a year before 1920 to seven months a year in the '30's and '40's was limited, last year, to a week or two. In February–March of this year we find the ice extending half way from Greenland to Norway, more extensive than ever recorded before and presumably comparable with some of the worst years of the seventeenth and eighteenth centuries (Plate I facing p. 270). The great tongue of ice in 1963 east and south-east of the island of Jan Mayen confirms guesses about the coldest climatic epoch which previously were thought by many to be rather bold.

One weighty element in the situation still remains virtually unaltered. Water temperatures in the broad Atlantic are close to the level of the 1920's and '30's despite a fall of 2°C from the peak level reached as late as 1950–54.

No meteorologist would expect an intimate relationship between the Arctic sea ice and British weather. Certainly not that every winter would be severe just because the ice margin up about 70 degrees north had come a good deal nearer. But the evidence from the past does suggest some relationship, and in particular that the oceanic influence on our climate is reduced at any rate in the colder seasons of the year.

There is another effect. Since snow and ice have a great power to reflect away (and so waste) the sun's radiation, one may suppose that the ice will not disappear as quickly as it formed. (There seems to be some support for this idea because a number of past climatic deteriorations were more abrupt than any of the recovery phases.)

Rather notable deteriorations of the climate of Europe and of the ice situation on the northern seas seem to have taken place in the mid sixteenth century, and again about 1740 and 1855. In each case what I have called cold winters, that is with temperatures generally below 3°C from December to February in central England, seem to have occurred 3 to 5 times a decade for the following half century or so, and the Arctic ice remained extensive. In one way, the situation that announced itself with the severe winter of 1564–65 was the closest parallel with that of today, because the Atlantic ocean was in all probability still rather warmer than it became between 1600 and 1900. That, incidently, was the winter that led Brueghel to start the tradition of painting the dramatic Flemish and Dutch winter landscapes (Plate II facing p. 271). 1564–65 probably matched the recent winter for severity: and this occurred at least 5 times within 200 years. It may have occurred about 10 times. In other words, the frequency of this degree of severity probably rose to once in 20 to 40 years, and in the 1600's even higher.

Studies of the prevailing wind circulation and its changes, which I have been conducting in the Meteorological Office, throw some light on the mechanism of all this. It turns out that the average strength of the world's main wind-streams in all latitude zones was increasing during the long-period climatic warming. That is to say, the general atmospheric circulation was waxing in vigour. The Atlantic depressions, with their thrusts of mild westerly winds from the ocean, were affecting Europe more, and were penetrating the Arctic more, as the ice retreated. The last two things went hand in hand. The mild air and storminess broke up, and restricted the growth of, the sea ice, and it could plausibly be argued that this opened up the area still more for the storm tracks.

Then a curious thing happened. From its peak about 1920 to 1930 the strength of the prevailing wind circulation began to wane again. Before long the depressions in this sector kept, to an increasing extent, to somewhat lower latitudes. We do not yet know the reason for this southward trend. It cannot be due to an extension of the ice because when it began the ice was, and for a decade continued to be, about its minimum extent. Perhaps it is something that happens automatically in this part of the hemisphere when the prevailing west winds weaken. This is not the occasion to discuss ideas about possible causes of the very long-term trend in the strength and prevalence of the westerlies. One aspect of it may be a cycle or oscillation eight or nine centuries long. But the trend away from the maximum strength of the westerlies and Atlantic storminess 30 years ago has already had some obvious consequences.

First, it has given the Arctic ice the chance to grow again. Secondly, it has meant that the Norwegian Sea has again become a favourite path for northerly winds at all times of the year to an extent unmatched for many decades past. This has helped to bring the ice forward. Thirdly, the accompanying southward trend of the depression tracks has brought the belt of frequent northerly and easterly winds nearer to this country. This has meant a rather narrow escape from severe weather in several recent winters, and most districts have had a considerably enhanced frequency of snow.

Depressions in summer have also shown a tendency to keep to more southerly tracks, between 55 and 65 degrees north, and this has produced some disappointing summers since 1954. It is a tendency that is likely to continue while the sea ice remains extensive. There is no rule about sizzling summers following severe winters. The best hope of a saving grace, if things go on this way, is that colder northern seas might favour rather more spells of what we call blocking anticyclones over the North Sea and Baltic in summer. In the later part of the cold epoch in the eighteenth century this apparently did happen sufficiently to make the peak summer months of July and August a shade warmer than in the best decades of this century. That meant a shorter, warmer summer, but of course it did not happen every year. In the 1500's and 1600's it was evidently much less frequent.

Recent changes in the ice situation, and the weakening of the general wind circulation that has been going on in the last three decades, suggest that our climatic situation now resembles that of the last century, or earlier, more than it does the recent warm decades. We should certainly be alert to possible advantages in changing our ways a little.

Editor's note.—Some repetition occurs in this article because it was originally a broadcast talk given by Mr. H. H. Lamb in the Science Survey series on the BBC Network Three (Thursday 2 May 1963) entitled 'Weather: Past and Future'. The talk was published in the *Listener* on 9 May 1963 and was mentioned very favourably by radio writer Lois Mitchison who found it interesting radio, especially since it merged a scientific background into a general picture without a flood of technical terms. We are grateful to the staff of the *Listener* for help in obtaining reproductions of the photographs used in the *Listener*.

CONFERENCE OF COMMONWEALTH METEOROLOGISTS MAY 1963

By A. A. WORTHINGTON, B.Sc.

The seventh Conference of Commonwealth Meteorologists was held at the Meteorological Office Headquarters, Bracknell from 7–10 May 1963. It was attended by delegates from most of the Commonwealth Countries and Colonial Territories. An observer from the Republic of Ireland was also present. The Conference was opened by the Rt. Hon. Hugh Fraser, M.P., Secretary of State for Air.

A feature of the Conference was its informality. Discussion was largely an exchange of views. The Conference provided more an opportunity for Directors of Commonwealth Meteorological Services to meet one another and draw on one another's experience in tackling problems rather than an occasion for arriving at conclusions.

The main discussions are summarized below:

(*a*) *Trends in meteorological services.*—Dr. A. C. Best opened by talking of the meteorological services in the United Kingdom. He pointed particularly to the changing pattern of requirement for meteorological services in aviation and the firm upward trend in requirements of the public services.

Opinion, as a whole, was that though the accent was perhaps no longer on meeting aviation requirements and that meteorological services in other fields—public services, public utilities, agriculture, hydrology etc.—had established or were establishing equal claims for consideration, this did not mean a falling off in aviation requirements; it meant rather an increasing recognition of the need for meteorological services in those other fields. It was felt that a proper assessment of the requirements of the various fields of meteorological service and the striking of a reasoned balance in meeting requirements was now, more than ever, important.

(*b*) *Numerical weather prediction.*—Mr. Knighting presented a paper on 'Numerical weather prediction'. The important point which he made was that the stage has now been reached when computed forecasts of isobaric surfaces for up to 24 hours ahead are as good as those produced by experienced forecasters.

(*c*) *Organization of research.*—Dr. R. C. Sutcliffe opened by giving an account of research in the Meteorological Office. He particularly stressed the advantages of a research organization within the Office; the close contact with the operational services; the awareness of the need for results which would be practical and of benefit in the provision of meteorological service; and he drew a parallel with the proved importance of scientific research departments in industry.

Dr. Sutcliffe was followed by Dr. McTaggart-Cowan who spoke of research in the Canadian Meteorological Service. Mr. Rao then gave an account of the place of research in the Indian Meteorological Service and Mr. Gibbs outlined the organization of research in the Australian Meteorological Department.

The general feeling was that there is a need for organized research and this more in the nature of team work rather than work of the individual.

(*d*) *The high atmosphere.*—Dr. R. Frith presented a paper on 'The high atmosphere', in which he gave a brief survey of the atmosphere between 30 and 100 kilometres.

(*e*) *The training of meteorologists.*—Dr. P. D. McTaggart-Cowan (Canada) opened by describing the system now in use in Canada. It had been found advantageous, in spite of the size of the country, to centralize meteorological training and the present system was an integrated one between the Meteorological Branch and certain of the universities. Moreover, by including training and research in one administrative division of the meteorological service, new advances and techniques had been more easily and quickly incorporated into the training curricula.

In discussion, special consideration was given to the role of universities. Practice varied between countries; some countries had developed an integrated system with the universities whilst in others meteorological training was given almost entirely in the training schools of the meteorological services. It was agreed, however, that meteorology should not be a mainly post-graduate subject and that the development of undergraduate courses in classical physics and environmental sciences, including meteorology, would be beneficial.

(*f*) *Agricultural meteorology.*—Mr. L. P. Smith presented a paper on the principles to be followed in agricultural meteorology. Two matters were of particular importance: firstly, the need for the closest possible co-operation between the meteorologist and the agriculturalist at every stage in the tackling of agricultural problems; secondly, the exercise of care in the choice of problems on which to concentrate. Priority should be given to those problems which seem capable of solution and the answers to which seemed likely to be of practical economic significance.

In the general discussion that followed, several interesting examples were given of the results of co-operation in agricultural problems. Mr. Smith described the success attained in the United Kingdom in the control of the liver fluke disease in sheep, and in the prevention of the growth and spread of applescab. Others told of the work on cotton planting problems in East Africa and the study of potato diseases in Ireland.

(*g*) *Assistance to meteorological services of Commonwealth Countries.*—The discussion, which was opened by Mr. Akingbehin (Nigeria) showed that in several Commonwealth countries which were about to become independent or had recently done so, there was difficulty in maintaining and developing the meteorological services due to shortage of financial and professional staffing resources. Aid under United Nations or bilateral schemes was inadequate and had to compete, within a limited budget, with pressing requirements in other fields.

(*h*) *Trends in the development of meteorological instruments.*—Dr. Robinson described briefly some of the activities within the Meteorological Office on the development of instruments intended for ordinary operational use. An exchange of views followed in which the main problems discussed concerned various aspects of radiosonde operation, including measures being taken to improve the increased height performance of balloons.

(*i*) *Meteorological satellites.*—Several directors reported on the uses made of information obtained from U.S. meteorological satellites, such as the location of tropical storms in areas of sparse surface observations and the study of ice

PLATE III—DELEGATES AT THE SEVENTH CONFERENCE OF COMMONWEALTH METEOROLOGISTS IN MAY 1963.

Standing, left to right: Mr. J. S. Sawyer and Mr. B. C. V. Oddie (United Kingdom), Instructor Captain J. R. Thorp (Naval Weather Service (NWS)) Mr. Hwang Tiaw Sooi (Singapore), Instructor Commander J. D. Booth (NWS), Mr. F. T. Hannan (Australia), Mr. E. G. Davy (Mauritius) Mr. J. P. Henderson (East Africa), Dr. R. C. Sutcliffe (United Kingdom), Mr. F. B. A. Giwa (Nigeria), Mr. S. E. Tandoh (Ghana), Mr. P. M. A. Bourke (Ireland, attending as an observer), Mr. P. J. Meade and Dr. A. C. Best (United Kingdom). *Sitting, left to right:* Mr. K. Rajendram (Malaya), Dr. I. E. M. Watts (Hong Kong), Mr. N. A. Akingbehin (Nigeria), Dr. P. D. McTaggart-Cowan (Canada), Sir Graham Sutton (United Kingdom), Mr. P. R. Krishna Rao (India), Mr. W. J. Gibbs (Australia), Dr. R. G. Simmers (New Zealand), Mr. J. O. Belford (Sierra Leone). (See page 273).

By courtesy of BOAC

PLATE VI—PRESENTATION OF METEOROLOGICAL AWARDS TO CAPTAINS OF CIVIL AIRCRAFT

Left to right: Captain B. J. Thwaites, D.F.C., Mr. P. J. Meade, O.B.E., Mr. A. M. A. Majendie, Master of the Guild of Air Pilots and Navigators and Captain Bernard C. Frost, O.B.E. (see page 282).

conditions on the oceans and large river estuaries. It was agreed however, that although satellite information was operationally valuable, it could not replace conventional observations or diminish the need for them. Indeed, to enable full value to be got from satellite data, better surface coverage was needed, particularly over those areas where the surface and radiosonde networks were now deficient.

(*i*) *Long range forecasting.*—In a general exchange of views it was agreed that the issue of reliable long range forecasts was the greatest contribution the meteorologist could make to a nation's economic welfare. Progress in this field had shown little sign of significant success but this must not cause a slackening of research and experiment.

Arrangements were made for the delegates to visit the
Central Forecasting Office
Meteorological Telecommunications Centre
Meteorological Office electronic computer
Instrument Development Branch
High Atmosphere Research Branch
Instrument and Equipment Building, Bracknell
Instrument Experimental Site, Easthampstead

The delegates also attended on one occasion the midday conference of the Central Forecasting Office. As relaxation from its discussions the Conference enjoyed the hospitality of the United Kingdom Government and of the Royal Meteorological Society.

551.509.317:551.577.38

THE 100 MB CHART AND DRY SPELLS AT LONDON (HEATHROW) AIRPORT

By N. E. DAVIS, M.A.

In a recent paper[1] the author cited a case in which a change in the circulation pattern at 100 mb was followed by a change in the weather type over the United Kingdom. The present note deals with the reverse of that situation and investigates the relationship between the 100 mb pattern and persistent dry weather at London (Heathrow) Airport.

The investigation was begun with an examination of the rainfall record at London Airport (51°29'N 00°27'W) for the period June 1960 to August 1962, during which time 100 mb charts had been drawn daily. Periods were classified as dry if no measurable rain fell over a period of three days or more. There were 52 dry spells comprising 349 days, 355 days with rain, but only 118 odd dry days. The lengths of the 52 dry spells were distributed according to the following table which gives the number of occurrences (in the period June 1960 to August 1962) of dry spells which lasted a specified number of days.

Length of spell in days	3	4	5	6	7	8	9	10	11	12	13	>13
Number of occurrences	9	11	8	2	5	3	3	5	1	1	2	2

The examination of the 100 mb charts for the 349 days within dry spells represented a considerable task and initially the investigation was confined to examining the cases when the dry spell lasted 10 days or more. Six of them occurred in the winter half-year and 5 in the summer—though all but three fell in the 4 months February 13 to June 10.

If there were any feature of the flow at 100 mb which was common to all these dry spells then it would be expected to show on a mean 100 mb chart.

Figure 1 shows the mean flow at 100 mb for the 5 occurrences in summer on the first day of a long spell. The first day of a long spell is defined as that day on which measurable rain had fallen during the 24 hours ending at 0600 GMT, but no measurable rain was thereafter recorded for at least 10 days. The mean flow was determined by estimating the 100 mb heights at 13 grid points in the vicinity of the British Isles from the completed 0001 GMT 100 mb contour map on the day in question, averaging over the 5 occurrences and drawing contours to fit these mean values. Figure 2 shows the mean flow for the second day of a summer dry spell, Figure 3 the mean flow for the fifth day and Figure 4 the mean flow for the last day.

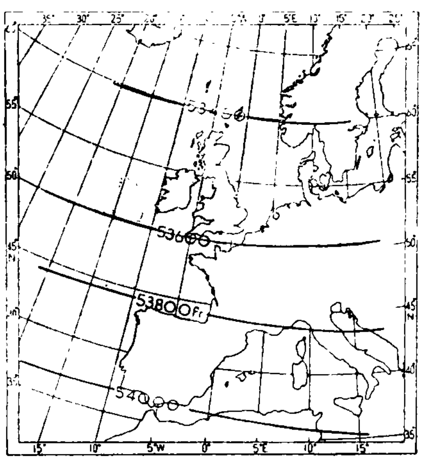

FIGURE 1—SUMMER DRY SPELLS—MEAN 100 MB CONTOUR CHART—FIRST DAY

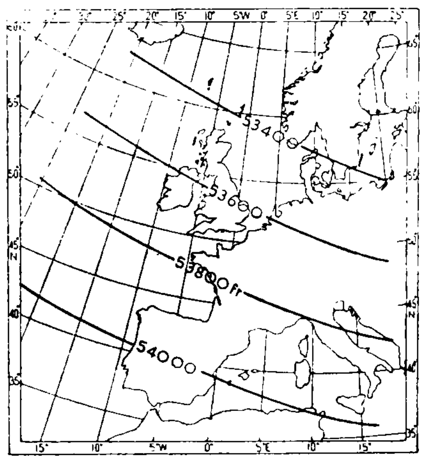

FIGURE 2—MEAN 100 MB CONTOUR CHART—SECOND DAY

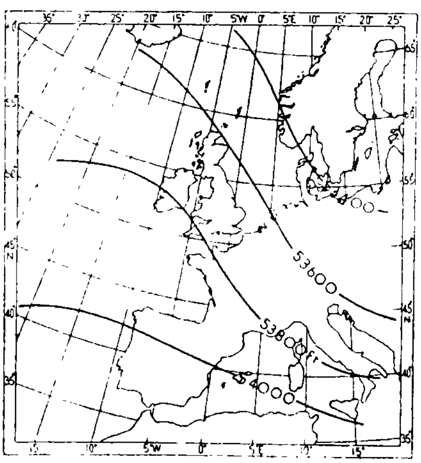

FIGURE 3—MEAN 100 MB CONTOUR CHART—FIFTH DAY

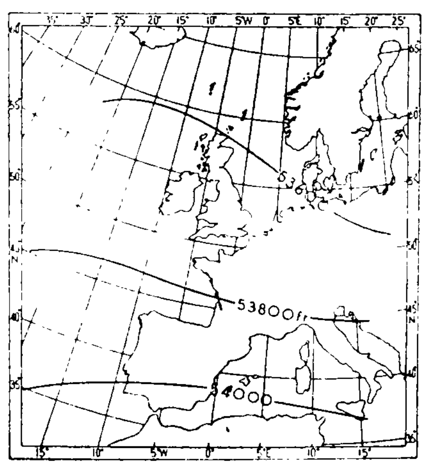

FIGURE 4—MEAN 100 MB CONTOUR CHART—LAST DAY

The mean flow is flat and featureless on the first day. This is not surprising as by definition measurable rain fell at some time during the 24 hours preceding 0600 GMT on the first day, so that it might even have been raining at chart time. On the second day however a definite ridge appears to the west of the British Isles and by the fifth day this has advanced eastwards—the axis then being located at about 15°W. By the last day the ridge has weakened considerably and moved across the British Isles to the North Sea.

Winter long spells show a similar story (Figures 5–8) except that the gradient is much stronger.

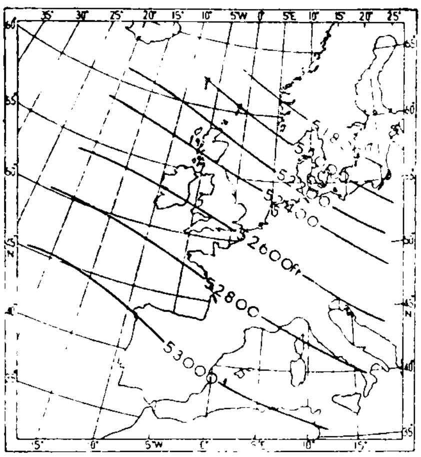

FIGURE 5—WINTER DRY SPELLS—MEAN 100 MB CONTOUR CHART—FIRST DAY

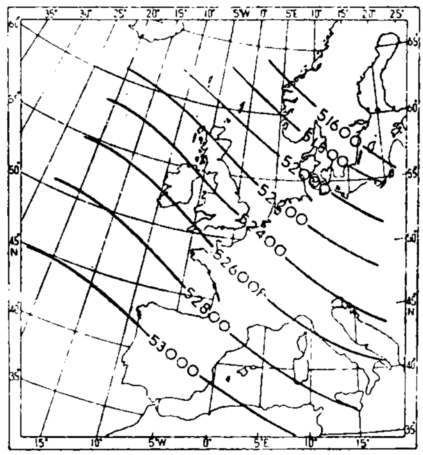

FIGURE 6—MEAN 100 MB CONTOUR CHART—SECOND DAY

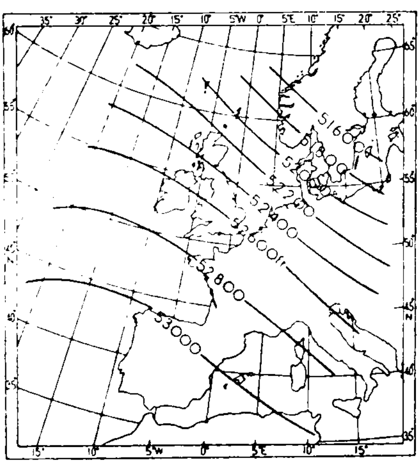

FIGURE 7—MEAN 100 MB CONTOUR CHART—FIFTH DAY

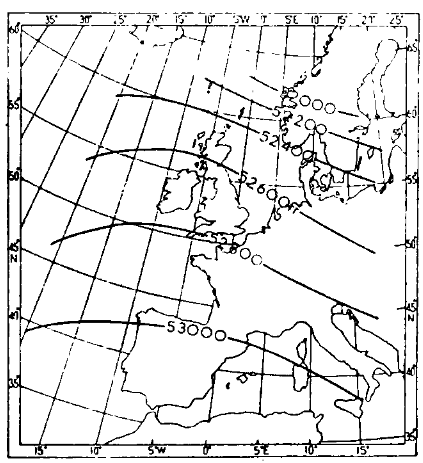

FIGURE 8—MEAN 100 MB CONTOUR CHART—LAST DAY

As it would appear from these mean charts that a ridge at 100 mb to the west of the British Isles is frequently associated with a dry spell at London Airport, an examination of the individual cases was made to see how the ridge arose. The axis of the ridge at 100 mb nearest to the British Isles was located at the positions of longitude and on the days quoted as shown in Table I.

TABLE I—LONGITUDE OF 100 MB RIDGE AXIS DURING DRY SPELLS OF TEN DAYS OR MORE

Date		Day 1	Day 2	Day 4	Day 5
			Summer		
			Longitude		
1961	7 May	12°W	12°W	12°W	13°W
	17 July	22°W	20°W	15°W	13°W
1962	24 Apr.	12°E	9°E and 29°W	17°W	14°W
	30 May	35°W	30°W	24°W	10°W
	30 June	27°W	30°W	33°W	33°W
			Winter		
1961	13 Feb.	5°W	2°E	2°E	3°E
	2 Mar.	1°W	5°W	6°W	5°W
	19 Mar.	34°W	32°W	27°W	20°W
	14 Nov.	23°W	12°W	18°W	11°W
1962	13 Feb.	45°W	34°W	22°W	20°W
	12 Mar.	12°W	20°W	22°W	20°W

After the first day, all cases show a ridge to the west of the British Isles (except 13 February 1961 when the ridge was just to the east). The ridge either moved slowly towards the British Isles (17 July and 19 March 1961, and 24 April, 30 May and 13 February 1962) or remained more or less stationary. The greatest speed of movement occurred during the dry spell of 30 May, when the associated ridge moved 20 degrees of longitude between day 2 and day 5, which at 55°N represents a speed of some 9 knots.

The number of cases considered (5 in summer and 6 in winter), is rather small and a further examination was made of those dry spells which lasted 7, 8 or 9 days. There were 8 of these in summer and 3 in winter. The axis of the ridge was located at the positions shown in Table II.

TABLE II—LONGITUDE OF 100 MB RIDGE AXIS DURING DRY SPELLS OF 7–9 DAYS

Date		Day 1	Day 2	Day 4	Day 5
			Summer		
			Longitude		
1960	15 June	14°W	8°W	5°W	14°W
	7 Sept.	18°W	10°W	6°W	3°E
	23 Sept.	30°W	22°W	9°W	5°W
1961	18 June	–	–	–	–
	3 July	27°W	27°W	30°W	28°W
	25 Aug.	25°W	3°E	3°E	2°W
1962	19 June	30°W	20°W	25°E	24°W
	27 July	15°W	8°W	20°W	8°W
			Winter		
1961	9 Oct.	16°E	9°E	5°W	5°W
	14 Dec.	5°W	5°W	7°W	8°W
1962	27 Feb.	19°W	29°W	33°W	48°W

These additional cases show much the same story except that 2 of the winter cases showed considerable retrogression, whilst during the dry spells of 19 June and 27 July 1962, two ridges moved across (at a speed of about 30 knots) with traces of rain during the passage of the weak trough between them. On the other hand during the dry spell of 18 June 1961, there was no ridge present. This dry spell began with a closed high cell over northern France which moved away southwards. The fronts which subsequently crossed southern England produced only a trace of rain at London Airport.

From the foregoing it would seem that there should be a definite correlation between the 100 mb wind direction over south-east England and rainfall at London Airport. The twelve months January–December 1961 were examined to test this. The wind direction reported by the radiosonde station at Crawley (51°05′N 00°13′W, 26 miles bearing 160° from London (Heathrow) Airport) was used when available, otherwise it was estimated from the chart. The winds were grouped into two sectors: 290°–020° (i.e. north-west and north) and 030°–280° (remaining directions). The following table gives the number of occasions of rain or no rain at London Airport for these two sectors. The wind direction was measured or estimated at 0001 GMT and the rainfall was measured for the 24 hours commencing 0600 GMT on the same day.

Wind direction at 0001 GMT	No rain measured in 24 hours commencing 0600 GMT on the same day	Measurable rain in 24 hours commencing 0600 GMT on the same day
	number of occasions	
290°–020°	121	38
030°–280°	104	102

This table shows a highly significant absence of rain with winds between 290° and 020° (significant at the one per cent level, even on the assumption that only one in six of the observations are independent). Of the failures, the majority were marginal in that though the wind was from the north-west sector either the trough line to the east was close to London Airport or the ridge to the west was very minor and moved across rapidly during the period.

If the 100 mb wind can be forecast to remain between 290 and 020 degrees (i.e. with a marked ridge to the west of the British Isles) there is a strong probability of dry weather. This use of the 100 mb chart is currently being tested by the production of experimental 4-day forecasts of precipitation at London Airport.

REFERENCE

1. DAVIS, N. E.; The 100 mb chart and a change of surface weather type near the British Isles. *Met. Mag., London*, **92**, 1963, p. 183.

551.510.7:551.513:551.574.1:061.3

SYMPOSIUM ON TRACE GASES AND NATURAL AND ARTIFICIAL RADIO-ACTIVITY IN THE ATMOSPHERE

By J. B. STEWART, B.Sc., D.I.C.

The Symposium was held at Utrecht in the Netherlands from 8–14 August 1962 under the joint auspices of the International Union of Geodesy and Geophysics and the World Meteorological Organization. In all 51 papers were presented, divided into four main groups:

(i) water vapour, oxygen-18, deuterium and tritium,
(ii) natural and artificial radio-activity other than tritium and carbon-14,
(iii) carbon dioxide and carbon-14, and
(iv) trace gases in the atmosphere.

It should be noted that this is a relatively new branch of geophysics—less than half a dozen measurements of the carbon-14 concentration were made before the nuclear tests held in the Pacific by the U.S.A. in 1952—so that the value of radio-active trace materials (in particular some of the naturally occurring ones), as research tools, is only just becoming appreciated. As a result, a considerable part of the symposium was taken up by the presentation of series of radio-activity measurements which could not be directly useful in meteorological problems. However, there was also a number of papers related to cloud physics and the general circulation.

Three papers were given which suggested the use of techniques involving isotopes in cloud physics research. Dr. Friedman (U.S. Geological Survey) presented data on the distribution of deuterium in water. He showed that the ratio of deuterium to hydrogen in the water of a condensed droplet depends on the temperature at which the droplet formed. He therefore suggested that by measuring the deuterium to hydrogen ratio of precipitation in clouds or just below cloud base, so that no evaporation could take place, it may be possible to determine the mean temperature at which the drops formed.

Dr. Rama (India) presented a paper suggesting that by measuring the concentration of radium C (half-life 19 minutes) in precipitation, it would be possible to deduce the life time of the drops. However, the interpretation of the results of these suggested methods will be complicated by the effect of the growth process of the precipitation drops. These drops are formed by accreting many other smaller drops which have greatly varying ages and temperatures of formation, thus there is no precise age or temperature of formation, only a spectrum of values.

Some French workers under M. Facy have also been using the deuterium to hydrogen ratio in cloud physics. To determine the life history of a hailstone, they measured the deuterium to hydrogen ratio of each layer, removed one at a time by sublimation under vacuum. These measurements then gave the temperatures at which the drops had been added on to form the layers. Thus the motion of the hailstone in the cloud is deduced. M. Facy presented the results of this technique used on a 20 millimetre diameter hailstone, which suggested that it had grown (from 4 mm diameter) while ascending to near the top of the cloud.

A number of papers presented work on the general circulation using trace gases.

Dr. Machta (U.S. Weather Bureau) used radon as the tracer. This is a natural radio-active gas with a half-life of 3.8 days, which is liberated only from the land masses. From measurements of the concentration at various heights above and below the tropopause, he computed the time for the radon to be transferred through the tropopause and hence the mean vertical velocities, which were typically of 100 to 400 metres per day.

Dr. Keeling (Scripps Institute of Oceanography) presented very comprehensive measurements of the carbon dioxide concentration taken from 90°N to 90°S over the Pacific. The distribution of the natural sources is known and the other source—industry—is almost entirely concentrated between 30° and 60°N. So, from these data, Dr. Bolin (Sweden) has been able to determine a mathematical model to describe the transfer of carbon dioxide from the northern to the southern hemisphere.

Dr. Newell (Massachusetts Institute of Technology, MIT) presented a long and detailed paper based on measurements of the wind and temperature structure over the world (part of the Planetary Circulations Project of MIT) and of the concentrations of radio-active material at heights up to 24 kilometres, and on some observations from the Meteorological Rocket Network at higher altitudes. From these data he has computed meridional cross-sections of the vertical motion, wind velocity and its variance for the four seasons. From data on fission-product radio-activity, tungsten-185 and ozone, he has deduced that eddy processes are of equal, if not of greater, importance than mean motions in redistributing trace substances throughout the stratosphere. His results agree generally with those of Murgatroyd and Singleton[1] and Tucker,[2] but not completely in detail.

A number of other papers, for example by Dr. Kalkstein (U.S.A.F. Cambridge Research Laboratory), Dr. Friend (Isotopes Inc.) and Dr. Machta (U.S. Weather Bureau), gave measurements of the concentration of various artificial radio-active fission products which have been introduced into the stratosphere. These measurements were then used to compute the time taken for transfer to the troposphere and from one hemisphere to the other. Typical of their results were those given in Dr. Kalkstein's paper. He found that the data indicated that there was fairly even distribution between the two hemispheres in the high stratosphere, i.e. at heights of 100 to 150 kilometres. From there the fission products were brought down to the lower stratosphere in high latitudes by mixing associated with the development of disturbances in the polar-vortex region. This was followed by circulation towards the lower latitudes at these lower altitudes.

Another radio-active material that appeared to be interesting was tritium. This is the naturally-occurring radio-active isotope of hydrogen, which has a half-life of 31 years. It is formed by cosmic rays in the high atmosphere. In the form of water vapour, the tritium diffuses down to the upper troposphere and then falls out as precipitation. Since the tritium becomes concentrated in the oceans, these then act as the apparent source. This isotope is thought to be useful in providing information about the hydrological cycle. Dr. Bolin (Sweden) has studied its distribution in precipitation using a network of collecting stations in Scandinavia. To obtain data on the global distribution of tritium, the International Atomic Energy Agency, with Dr. Eriksson in charge, is setting up a network of 90 stations, 60 in continental areas and 30 in oceanic areas (ocean weather ships and Pacific islands). The preliminary analysis will probably be carried out in Sweden. These data will probably be sufficiently detailed for hydrologists, but for any meteorological work, a more complicated programme would be required. This would entail measuring other radio-active materials in the precipitation as well as the tritium content and also the tritium concentration in water vapour.

Other interesting lectures were those by Dr. Möller (Germany) on the effects of variation of carbon dioxide, by Dr. Junge (Germany) on strato-spheric aerosols and by Dr. Chamberlain (Harwell) on the interchange of iodine between air and vegetation.

The papers presented at this symposium have now been published.[3]

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1. MURGATROYD, R. J. and SINGLETON, F.; Possible meridional circulations in the stratosphere and mesosphere. *Quart. J. R. met. Soc., London*, **87**, 1961, p. 125.
2. TUCKER, G. B.; Mean meridional circulations in the atmosphere. *Quart. J. R. met. Soc., London*, **85**, 1959, p. 209.
3. American Geophysical Union. International Symposium on trace gases and natural and artificial radioactivity in the atmosphere. *J. geophys., Washington, D.C.*, **68**, 1963, p.3745

NOTES AND NEWS

Meteorological Office awards to captains and navigators of civil aircraft

On Thursday, 11 July 1963, the annual Meteorological Office awards for 'long and meritorious service in the provision of weather reports from aircraft' were presented to Captain Bernard C. Frost, O.B.E., the flight manager of the BOAC 'Seven Seas' fleet and to Captain B. J. Thwaites, D.F.C., a senior captain of the Comet flight of BEA. The presentation ceremony took place at the Royal Aero Club, Fitzmaurice Place, London, W.1 under arrangements made by the Guild of Air Pilots and Air Navigators with the Master of the Guild, Mr. A. M. A. Majendie, M.A., F.R.Ae.S., F.I.N., F.R.G.S. presiding. Mr. P. J. Meade, O.B.E., Deputy Director (Outstations Services), Meteorological Office, presented each captain with a briefcase on behalf of the Director-General of the Meteorological Office. (See Plate IV facing p.275)

Before making the awards Mr. Meade thanked the Guild for their continued support in sponsoring the presentation ceremony each year and, on behalf of the Director-General, invited the Guild to visit the new Meteorological Office Headquarters at Bracknell. Mr. Meade described the awards as a small acknowledgement of the debt which meteorology owed to aviation. With the coming of aviation the importance of meteorology grew enormously. As aviation developed, the demands upon meteorology increased and this led to vast extensions of our knowledge of the atmosphere and also to advances in forecasting. Observations formed the essential basis for forecasting and for many years aircrews had given invaluable help in providing meteorological services with weather reports in flight which were used to supplement the data obtained from the national reporting networks.

Presenting the awards, Mr. Meade said that Captain Frost had an outstanding record of weather reporting over more than twenty years. He was extremely well known to meteorologists because of the keen interest he had always shown in the problems of aviation forecasting. Captain Thwaites also had an excellent record for weather reporting over many years and Mr. Meade recalled with pleasure that Captain Thwaites had spent a short period in the service of the Meteorological Office before joining the RAF as a pilot during the last war.

Finally, Mr. Meade thanked BEA, BOAC and the Independent Air Lines for encouraging pilots to make weather reports in flight and took the opportunity of expressing gratitude to the Corporations for granting facilities for forecasters to make familiarization flights over air routes. He mentioned especially Mr. Chambers and Mr. Wood, the Meteorological Superintendents of BOAC and BEA respectively, and said that the Meteorological Office valued very highly their advice on all aspects of aviation meteorology.

The Director-General is also awarding books to the following for their weather reports: Captains R. H. Payne, D. B. Wilkie, P. Bray and D. B. White of BEA; Captains G. Thomas and P. Siegel of British United Airways; Captain C. M. Argles of Morton Air Service; and Captains G. R. Buxton, L. O. Barnett, T. M. Bulloch and D. B. McGregor of BOAC. Similar awards go to BOAC navigators T. A. Anderson, D. E. Campbell, J. G. Goodwin and J. E. Goulden.

REVIEWS

Vegetation and hydrology, by Dr. H. L. Penman, O.B.E., F.R.S. 8½ in. x 5½ in., pp. viii + 124, Commonwealth Agricultural Bureaux, Farnham Royal, Bucks., 1962. Price: 20*s*.

In this admirable survey Dr. Penman discusses one of the most important and perplexing aspects of the hydrological cycle, the role of vegetation in the cycle with particular reference to the disposal of soil moisture. It is important because the management or mismanagement of vegetation presents man with what is at present his most effective opportunity to alter the natural hydrological cycle. It is perplexing because, as the welter of conflicting evidence and opinion gathered in this book shows, the circulation of moisture in and through the soil is still imperfectly understood.

The first chapter discusses the general problem, akin to that of the hen and egg, of whether vegetation is the result of rainfall or whether rainfall can be induced by vegetation. Circumstantial evidence is generally in favour, and meteorological evidence overwhelmingly so, of the belief that vegetation is the result and not the cause of precipitation.

In the second chapter which is devoted principally to the interception of precipitation by vegetation and the disposal of the intercepted water, the author has a cautionary note on the problem of adequate exposure of a rain-gauge and on the incautious use of rainfall data in assessing general rainfall over an area.

Infiltration, run-off and erosion are discussed briefly in Chapter 3. Erosion is a world-wide problem and requirements for its prevention or reduction are high infiltration rates and minimal surface run-off. Experimental data show clearly that forest floors or humid pastures afford the greatest protection against erosion, and row crops or fallow the least. Reference might have been made in this chapter to wind erosion which is generally complementary to water erosion and may be the dominant form in arid regions.

The key chapter to the book is the fourth, where the most important part of the hydrological cycle, the transfer of water vapour to the atmosphere, is very succinctly and ably discussed. After a brief reference to the biological approach to the transpiration of water, the author deals with evaporation as a weather phenomenon, first discussing the basic physical problems and then referring to special difficulties which include temporal difficulties (different lengths of growing seasons), edge effects, crop management, anomalous stomata closure, interception differences and many others. Of the numerous evaporation formulae, four are discussed in some detail (those of Blaney and Criddle, Thornthwaite, Turc and the author). After reference to evaporation from bare soil (where evaporation rates are quickly reduced with drying out of the top few centimetres of the soil, and the amount and frequency of rainfall is the only weather factor of importance), the author introduces the concept of potential transpiration. He discusses the strong clash of opinion among experts as to whether soil moisture is freely available from transpiration by plants up to a point at which growth and vigour cannot be maintained, or whether the actual rate of transpiration falls below the potential shortly after the start of drying out of soils. This question of the availability of water is one of great importance in water balance studies and is an aspect of the soil-moisture problem about which, at present, almost all evidence is empirical.

The last three chapters deal with (i) water-use when water supply is non-limiting, (ii) evaporation at and between extremes of water supply and (iii) experiments on water-use on catchment areas. These chapters are valuable for the presentation of a great amount of data, drawn from truly world-wide experience, on water-use by vegetation.

The reviewer takes issue seriously with only one of the opinions expressed by the author where (page 103) in discussing a water balance study of the Sperbelgraben and Rappengraben (Switzerland) catchments, he says it is doubtful if any meteorologist would accept either part of the assumption that rainfall at any altitude inside a catchment area is the same as that outside at the same altitude, and the catch of any gauge is the mean catch over an altitude range of the order of ± 500 metres. On the contrary, with regard to the first part of the assumption, it has been the practice from the earliest days of the systematic study of rainfall in Britain to extrapolate isohyets in this way and data obtained subsequent to the drawing of isohyetal maps by such workers as Mill, Carle Salter and Glasspoole have shown how accurate such extrapolation can be. The second part of the assumption made in the Swiss paper is perhaps more open to doubt but at least the assumption shows an awareness that rainfall varies with altitude and that some allowance should be made for this fact. Indeed, it is felt that many water balance studies have been vitiated from the start by unsophisticated use of rainfall data. All too frequently one reads of experimental studies in rugged terrain where estimates of area rainfall are based on readings of a single gauge or the arithmetic mean of a few gauges. The author is, of course, aware of this problem in general and, as has been noted, refers to it in Chapter 2.

The book is written with great economy of style, with scarcely a word wasted, and this, coupled with the great amount of tabular data needing careful study, demands a very close though fully rewarding attention from beginning to end. A valuable bibliography of some 300 references is included.

J. GRINDLEY

Exploring the atmosphere, by G. M. B. Dobson. 8½ in. x 5½ in., pp. xi + 188, *illus.*, Clarendon Press, Oxford., 1963. Price: 21*s*.

Hoar frost and noctilucent clouds; fine weather potential gradient and the aurora; carbon dating and solar flares; there is something about all of them in this little book. The whole of the earth's atmosphere from the surface up to heights of 10,000 kilometres and above is surveyed. Inevitably the treatment must be superficial; here and there it is facile—as in the account of anticyclonic inversions—and there are indications that the volume was hastily written. However the chapters on the higher parts of the atmosphere, especially those on ozone, aurora, airglow and the ionosphere, provide a useful and simple introduction to these regions.

There are no references nor any suggestions for further reading.

R. FRITH

OFFICIAL PUBLICATION

The following publication has recently been issued:

Pictorial guide to the maintenance of meteorological instruments, London, HMSO, 1963. Price: 10*s*.

This book has been compiled on the assumption that, if a task is made easy, more people who attempt it will achieve results. The presentation is in picture form; technical names of instrument parts are not common knowledge and the parts to which these names apply are indicated on the diagrams. The directions are based on those given to students arriving at the Meteorological Office Training School, some of them with no previous knowledge of meteorology and most of them having little experience with instruments.

The methods used to keep the instruments in good order are those the author has found to be efficient during 21 years in the Meteorological Office both in the British Isles and abroad. The ideas are sometimes original but a great deal was learnt in the Meteorological Office Instrument Branch test room. The section on fault-finding is intended to stimulate critical examination of charts and, with the rest of the book, teach a technique of maintenance which will be applicable to meteorological instruments in general.

Observers at independent meteorological stations, especially those who supply information to the Meteorological Office, may find this book useful; students from foreign countries who have attended instrument courses at the Meteorological Office Training School have found that a poor command of English is less of an obstacle when using this publication.

PUBLICATION RECEIVED

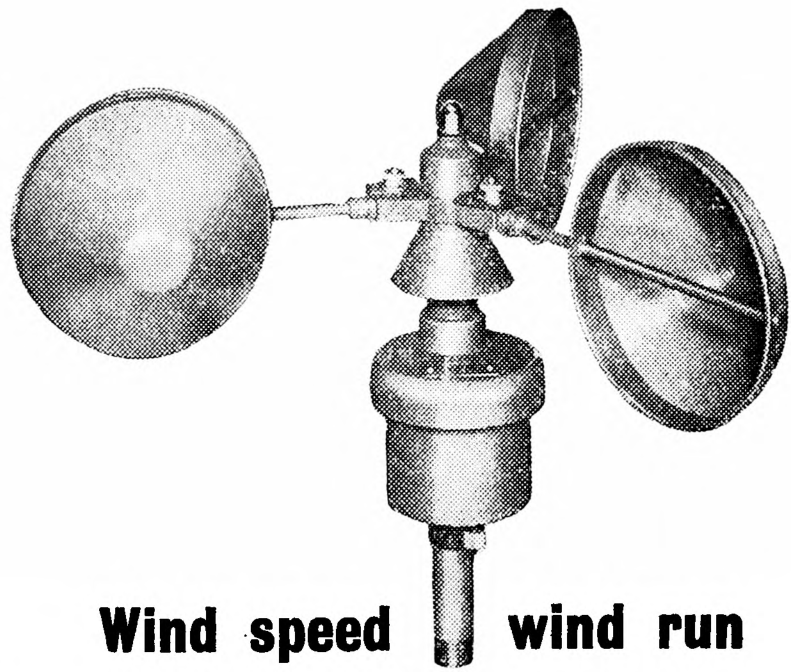
The Weather: formation of clouds (in the series "Geography–Meteorology"). 30 in. x 40 in., Wallchart (C.857) in three colours, Educational Productions Ltd., East Ardsley, Wakefield, Yorkshire, 1962. Price: 10*s*.

METEOROLOGICAL OFFICE NEWS

Bracknell Chess Club.—The Bracknell Meteorological Office Chess Club in their first year of competitive chess, have succeeded in leading Division II of the Berkshire County Chess League for 1962–63.

CORRIGENDA

Meteorological Magazine. Vol. 92, p. 219, on line 24 for *ue* read *uφ*.



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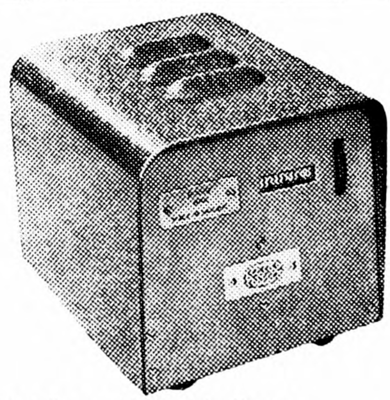

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THE METEOROLOGICAL MAGAZINE

Vol. 92, No. 1095, October 1963

551.509.318:551.547.5:551.557.5

DEVELOPMENT OF THE JET STREAM AND CUT-OFF CIRCULATIONS

By C. J. BOYDEN

Summary.—The changes in the 300 mb flow leading to the development of jet streams are described, and it is found that jet streams in middle latitudes usually occur through deformation of a single baroclinic flow rather than by confluence of two air streams. Working rules are presented for forecasting the development and movement of cut-off highs and lows at the 300 mb level on the basis of the jet-stream pattern and the shape of the 500–300 mb thickness lines.

The development of a jet.—It is not the purpose of this paper to discuss theories of jet-stream development but rather to recognize associated developments which are of use in jet forecasting. It is necessary, however, to make brief references to existing theories because of the sequence of events which they postulate. A theory put forward by Rossby[1] was based on the constancy of absolute vorticity during lateral mixing. This involves a southward increase of relative vorticity culminating in a sharpening of the zonal wind speed profile in middle latitudes. In so far as the jet stream of middle latitudes is concerned this explanation is supported by Palmén.[2] On the other hand Namias and Clapp[3] propounded the confluence theory in which thickness lines and contours become concentrated where cold air from the north is brought to flow beside warm air from further south. The confluence which concentrates the flow results basically from a wave train in one latitude overtaking a wave train in another.

The present study led to the conclusion that, whatever may be the broad-scale mechanism leading to the development of a strong upper wind belt, the final stage in the development of a jet is much as described by the University of Chicago group[4] in 1947. It was found that a jet usually developed through confluence on the east side of an upper ridge or trough but not in the way suggested by Namias and Clapp.[3] In most cases the jet formed within a single amplifying flow, independently of the existence of a confluence with a stream of air of different origin.

An analysis was made of jet streams occurring in four winter months chosen at random. Occasions were noted when jets developed *in situ*, as distinct from those when jets spread downstream or laterally into the area. There were 32 such jets which were located where profiles of the 300 mb wind speed could be drawn. In each case, an estimate was made of where on the profile the trajectory from any upstream split of the airstream should be found. The position of this was then compared with the position of the peak wind speed.

As far as could be ascertained, the confluence of different airstreams was the main cause of one of the 32 peak winds and a contributory cause of three others. Twenty-nine of the 32 jets developed mainly in association with a concentration of thickness lines on the east side of an upper ridge or trough. It is therefore considered that the great majority of jets develop through an intensification of the thermal gradient which accompanies the buckling of the flow pattern as described in the following paragraphs, a second airstream not being involved.

Figure 1 (*a*) depicts a uniform belt of moderate or strong upper winds in which the thickness lines, shown by broken lines, lie along the flow. Figure 1 (*b*) shows the beginning of an oscillation, perhaps associated with upstream cyclogenesis or with the approach of a thermal trough causing a sympathetic troughing of the contours. It is clear from the direction of the wind at A and

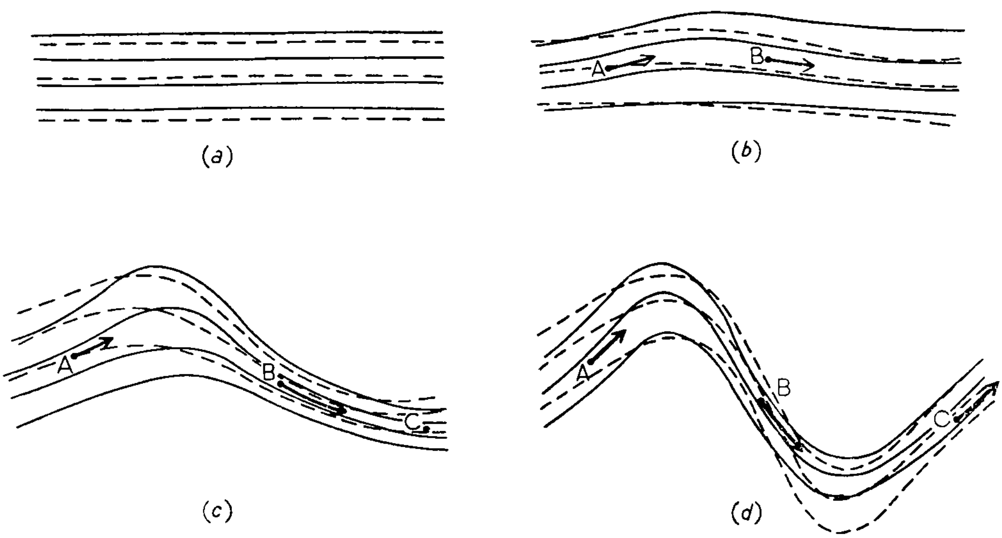


FIGURE 1—THE DEVELOPMENT OF JET STREAMS

———— contours - - - - thickness lines

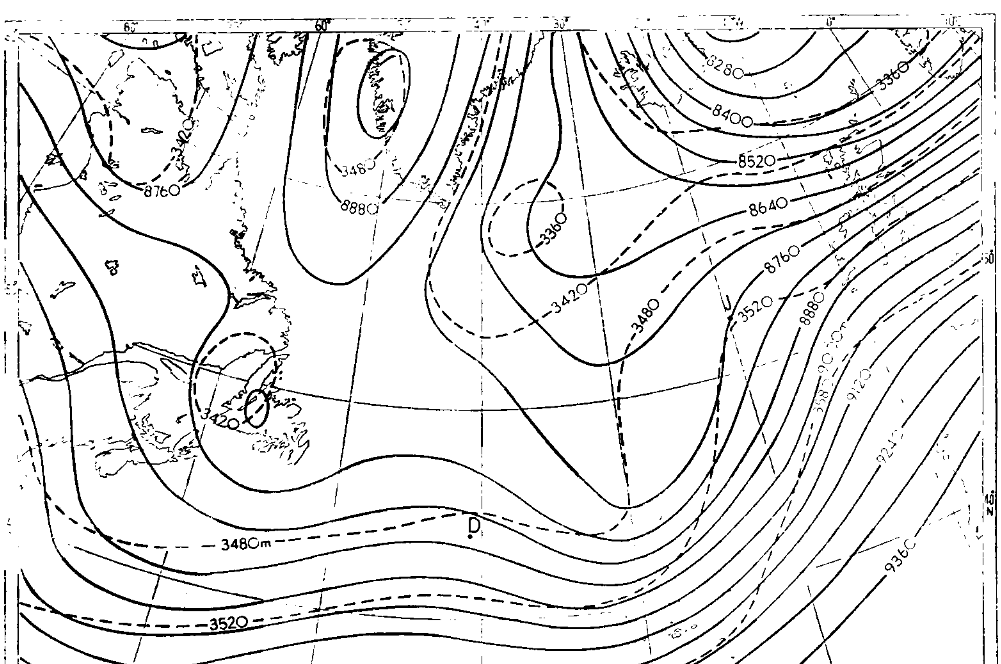
Arrows represent wind at points A, B and C

B that the thickness lines must begin to take up the oscillation, and thermal advection in turn induces an oscillation in the contours, so the development becomes self-generating. The advection across thickness lines is seen to be greater upwind of B than it is at B, so, as shown in Figure 1 (*c*), a concentration of thickness lines develops in the region of B. Thus the thermal ridge and the contour ridge become asymmetrical and remain slightly out of phase. On most occasions the advection of warm air and therefore the rise of 300 mb height are greatest to north-west of B, so the jet at B usually veers. A weakening and backing of this jet are to be expected if the supply of warm air is cut off, and this sometimes occurs when a cold pool or the remnant of one interrupts the flow of warm air. The usual veering of the jet at B backs the thickness lines through C and they become a concentrated band leading to the development of a south-westerly jet at C as shown in Figure 1 (*d*). This process can be perpetuated further, the older jets usually weakening from various causes, but it is more likely that the train of waves will be interrupted by the development of a cut-off low or, less frequently, by a cut-off high.

The 300 mb chart of 0000 GMT on 4 December 1961, reproduced as Figure 2(*a*), shows a typical development. At this time a trough in the longitude of Bermuda was beginning to develop, and 24 hours later (Figure 2(*b*)) there was strong warm advection on the east side of ocean weather station "D", accompanied by a sharpening of the 300 mb ridge. Within a further 24 hours the advective warming had reached ocean weather station "J" and the chart of 0000 GMT on 6 December (Figure 2(*c*)) shows a strong north-westerly jet there. There is clear evidence that this marked increase of wind was a feature of the ridge and followed the arrival of warm air, and there is no evidence that the confluence with the air from Greenland played any part in the development of the jet. On this occasion there was little intensification of the south-westerly wind over Europe, mainly because the north-westerly jet led to the formation of a cut-off low over the Mediterranean.

The chain of events described above is presented without any dynamical explanation but will be recognized as the downwind propagation through the pattern of an intensification and amplification of the flow. This type of pulsation was studied by Rossby[5] and he showed theoretically that such a feature should have a 'group velocity' in excess of the zonal wind speed.

It is not uncommon to find two parallel jets within a few hundred miles of each other. This sometimes occurs ahead of a pair of warm fronts but the jets are more likely to be found on either side of a confluence of two separate airstreams, one jet being associated with a cold front and cyclonic flow, the

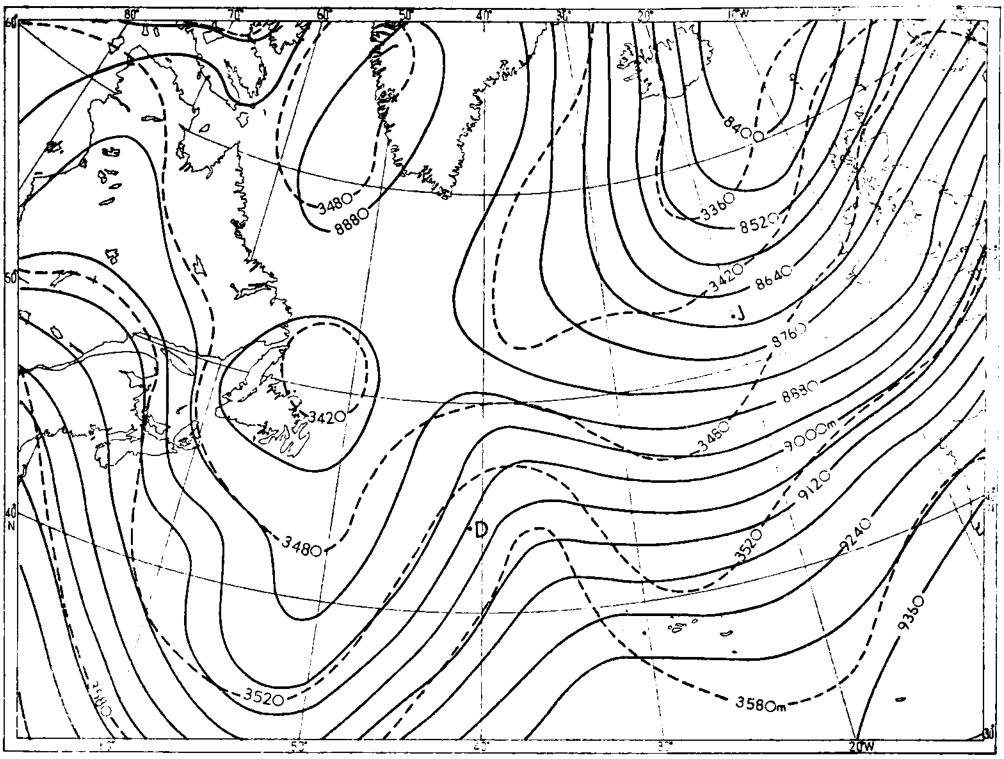


2(*a*) 0000 GMT on 4 December 1961

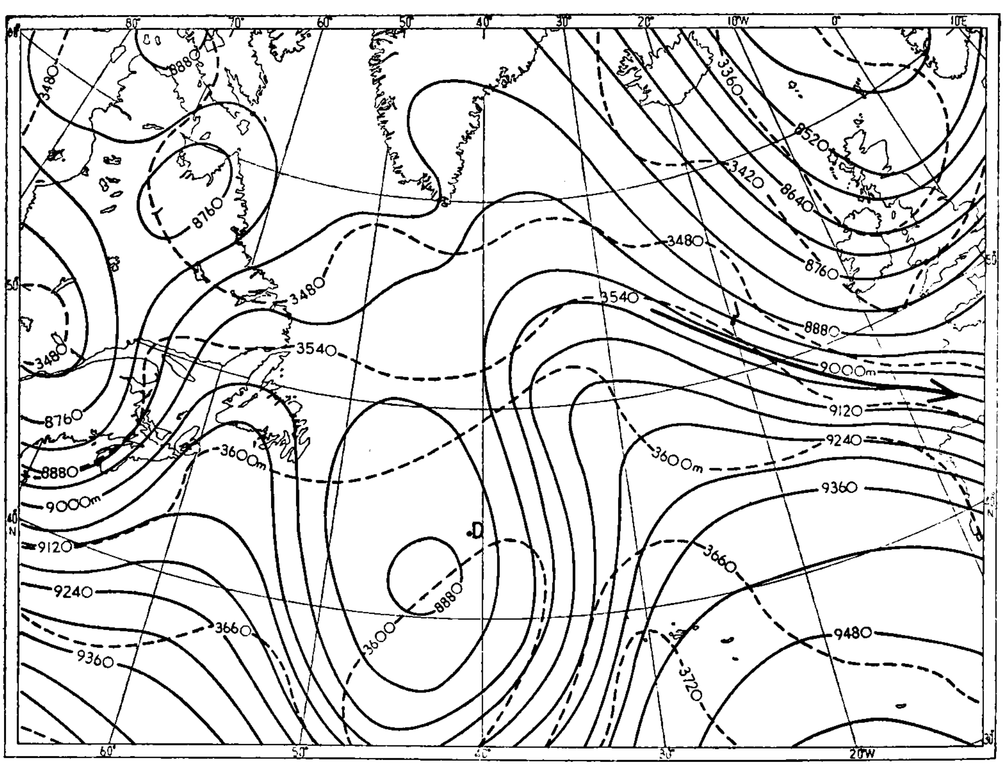
FIGURE 2—THE DEVELOPMENT OF A NORTH-WESTERLY JET IN WARM AIR

——— 300 mb contours - - - - 500–300 mb thickness

J and D are ocean weather stations.



2(*b*) 0000 GMT on 5 December 1961

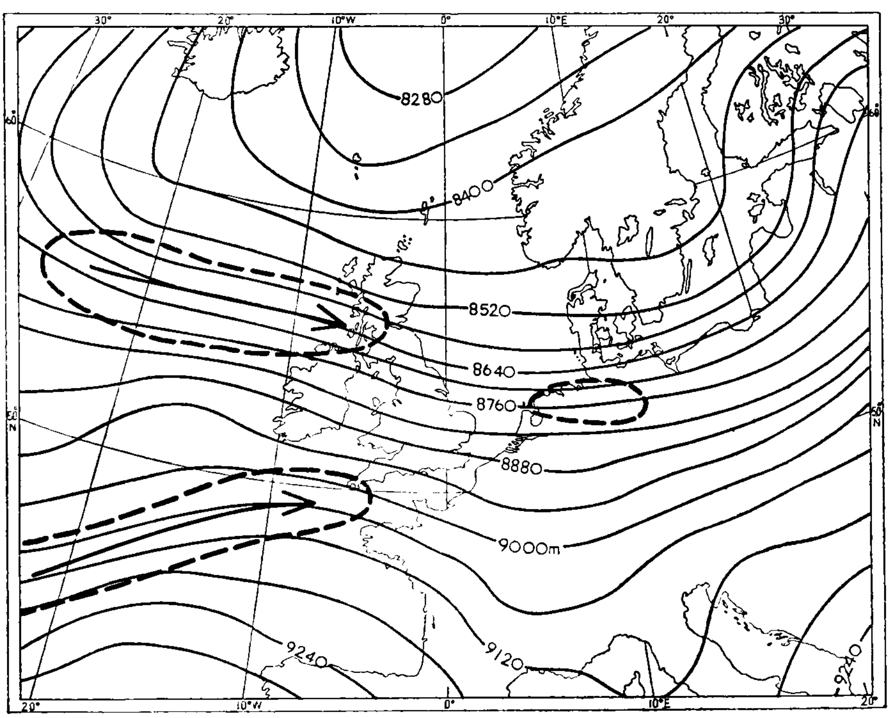


2(*c*) 0000 GMT on 6 December 1961, bold arrow indicates position of jet stream.

FIGURE 2—THE DEVELOPMENT OF A NORTH-WESTERLY JET IN WARM AIR

other with a warm front accompanying an upper ridge. Because of the confluence, the jets probably draw nearer to each other and may eventually be regarded as a single jet produced by the confluence, the true evolution being lost in the process of simplifying the analysis. An example of this is shown in Figure 3. The 300 mb chart for 0000 GMT on 3 December 1961 (Figure 3(*a*)) shows a warm jet approaching south-west England and a cold jet approaching west Scotland. The broken lines show the main 100 knot isotachs, though these are inevitably somewhat uncertain. Twenty-four hours later (Figure 3(*b*)) both jets had propagated downstream and drawn closer to the confluence. By 1200 GMT on 4 December (Figure 3(*c*)) the cold jet had moved quickly to Scandinavia and the warm jet had moved north to the Midlands, so for practical purposes there was now a single jet, though with variations along it of wind speed and probably of height. This amalgamation of jets is favoured by some buckling of the flow but it is more usual for the two to retain their separate identities and move side by side for as long as wind continues at jet speeds.

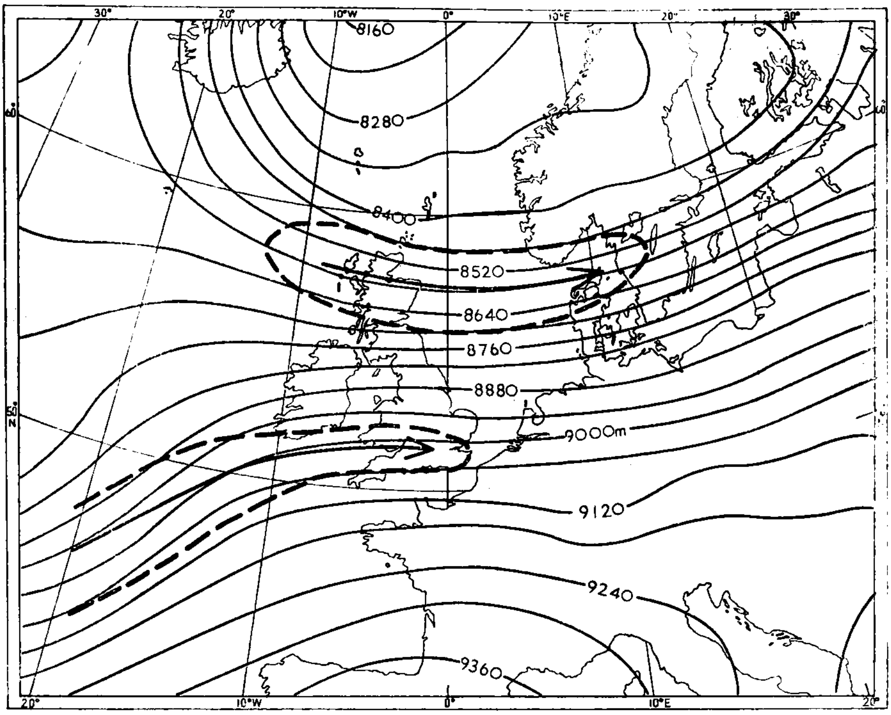
The development of cut-off circulations.—Closed circulations at upper levels are formed in a variety of ways, sometimes by the upward growth of low-level systems and sometimes initially as features of the upper flow. A closed circulation appearing first in the middle or upper troposphere develops when a zonal flow becomes meridional, with the result that there is an increase



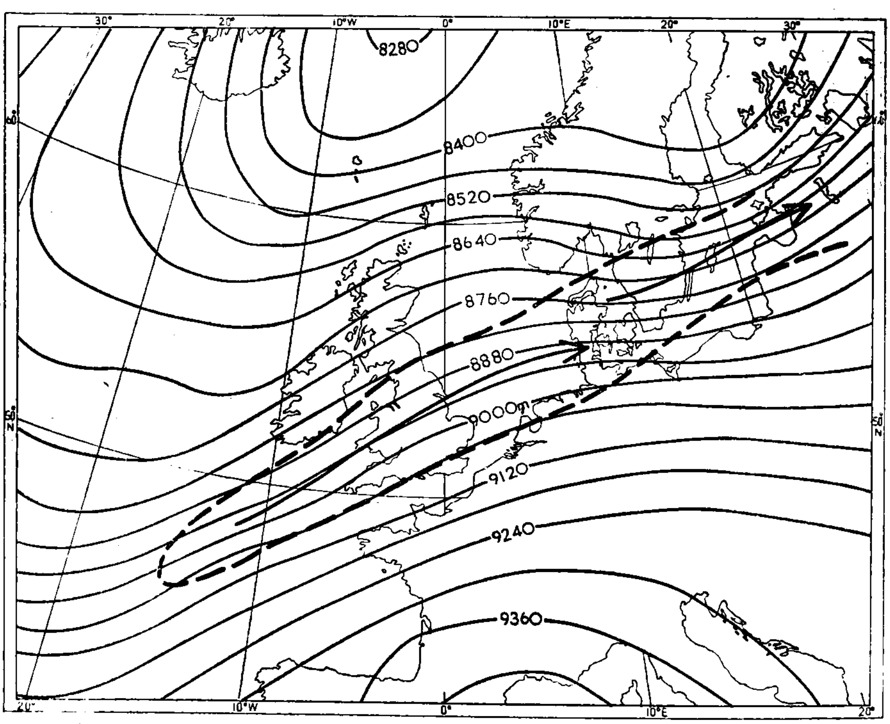
3(*a*) 0000 GMT on 3 December 1961

FIGURE 3—THE AMALGAMATION OF TWO JET STREAMS

——— 300 mb contours — — — 100 knot isotachs
Bold arrows indicate the position of the jet stream



3(*b*) 0000 GMT on 4 December 1961



3(*c*) 1200 GMT on 4 December 1961

FIGURE 3—THE AMALGAMATION OF TWO JET STREAMS

of relative vorticity in low latitudes and a decrease in the north. The mechanism of cut-off circulations is a study with which the name of Palmén,[2,6] is particularly associated. The precursors of cutting-off have long been recognized as a northward surge of warm air and a southward surge of cold air. The following sections are concerned with recognition of the indications that such a surge is about to lead to a closed upper circulation, and the subsequent behaviour of the systems is discussed briefly.

Cut-off highs at the 300 mb level.—The formation of a 300 mb ridge is associated with the northward movement of warm air. The temperature rise at a fixed point is most rapid when the northward movement is due to a jet. The reason for this is not only that the advecting wind is strong, but primarily that a fairly strong upwind temperature gradient usually exists to the right of a jet since the concentrated thickness lines of the jet from a southerly point usually turn away to the right. The transformation of the ridge into an upper high isolates a pool of warm air and the ridge is renewed to south of the detached circulation. A cut-off high may exist without any low-level counterpart, and its importance arises mainly from the diversion of the upper flow and the subsequent effect of this on low-level systems.

In order to determine conditions for cutting-off, a study was made of 300 mb charts over the North Atlantic and Europe during the months October to March from October 1959 to March 1962. An analysis was made of all highs that formed in a region where observations were adequate to decide whether a closed circulation developed. No account was taken of highs which entered the area as closed circulations. A few highs which appeared almost fortuitously through a small change of height in an area of light winds were also disregarded. Highs which lasted for less than 24 hours were treated separately and were regarded as forecasting failures if they conformed with the rules for formation.

In all there were 52 highs, of which 45 persisted for 24 hours or more. All 52 were preceded by jets from some southerly point, so it is reasonable to regard the existence of a jet as necessary for a high to form.

Amplitude of the thermal ridge.—The extent of the northward flow of warm air was noted in terms of the amplitude of the 500–300 mb thermal ridge. This was obtained by measuring, on the thickness line through the jet, the latitude difference between the thermal trough upwind of the jet and the thermal ridge downwind of it, the measurement being made 12 hours before the high appeared. Figure 4 shows the frequency distribution of

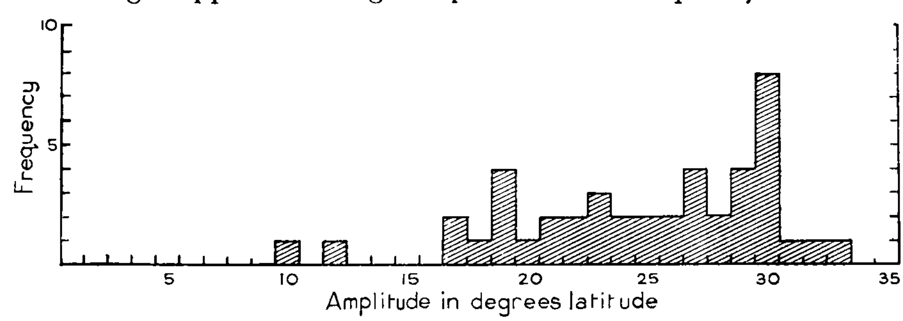


FIGURE 4—DISTRIBUTION OF THERMAL AMPLITUDES 12 HOURS BEFORE HIGHS BECOME CUT-OFF

amplitudes accompanying 44 of the 45 highs (the other already having a warm pool). Only two highs formed following an amplitude smaller than 17° latitude, and this is the only useful information provided by the diagram. The probability of cut-off increases to a well defined peak at an amplitude of 30° latitude but the drop beyond it may indicate no more than a climatological extreme to the amplitude of a thermal ridge.

Shape of the thickness lines.—Since cutting-off is characterized by an abrupt change in shape of both contours and thickness lines it was thought that the 500–300 mb thickness lines would give some indication of its imminence. A distinction was therefore made between ridge-shaped thickness lines and thickness lines which had become bulbous at the top of the ridge. The existence of a thickness bulb was defined by two short sections of a thickness line being parallel to each other on opposite sides of the ridge. The time elapsing between the appearance of a thickness bulb and the appearance of a cut-off high is shown in Table I.

TABLE I—PERIOD BETWEEN FIRST APPEARANCE OF A THICKNESS BULB AND OF A CUT-OFF HIGH

Number of hours between thickness bulb and cut-off high	Number of highs lasting 24 hours or more		Number of highs lasting less than 24 hours	
	With jets from south or east of south	With jets from west of south	With jets from south or east of south	With jets from west of south
0	1	–	–	–
12	11	7	–	1
24	8	10	2	2
36	2	1	–	2
48	1	2	–	–
60	1	–	–	–
Uncertain	–	1	–	–

From this table the following points are noted:

(i) The thickness bulb gave at least 12 hours' warning of cut-off on 50 occasions out of 52.

(ii) Seven of the 52 highs were transient.

(iii) The time lag was greater with jets from west of south and there were more transient highs than with south-easterly jets.

(iv) About 80 per cent of the highs formed 12 or 24 hours after the thickness bulb first appeared.

Direction of the jet.—Longer warning of cut-off can usually be given by forecasting the development of the thickness bulb. Its formation is clearly favoured by a backing of the jet since this produces an advective backing of the thickness lines on the west side of the thermal ridge. Of the 24 south-easterly jets in the second column of Table I, 23 backed in the 24 hours before the high formed, the remaining one showing no direction change. The mean backing on the 11 occasions for which 12 hours' warning was given was 56°, as against 21° for the 8 situations in which a thickness line was bulbous 24 hours before cut-off. On the other hand, the 21 south-westerly jets of column three showed a backing (averaging only 20°) on 8 occasions, a steady direction on 10 and a veer on 3.

There seems to be no doubt that the distinction between south-easterly and south-westerly jets introduced in Table I is related dynamically to cut-off as well as statistically. An analysis was made of jet directions at the time each of the 45 lasting highs formed, the measurement being made in the strongest part of each jet. The distribution is given in Table II.

TABLE II—FREQUENCY OF UPPER HIGHS IN RELATION TO DIRECTION OF JETS

Jet direction (degrees)	090	100	110	120	130	140	150	160	170	180	190	200	210	220
Number of jets	2	–	–	3	3	11	3	1	1	1	6	8	5	1

The high frequency of south-south-west jets is to be expected though the concentration of directions between 190° and 210° is perhaps surprising. The sharp peak at 140° is of greater interest and it is suggested this may be due to the fact that when a wind backs to about 140° its constant absolute vorticity trajectory no longer gives a continuing eastward movement but intersects itself, the air thus making virtually a closed circulation on the north-east side of the jet.

On 29 of the 31 occasions when the jet backed in the 24 hours before cut-off the backing took place in advance of a trough of which the jet constituted the eastern limb, or in one or two cases in advance of a small low. Thus the first sign that a thickness line is likely to become bulbous may be found upwind of the jet. Besides its effect on thickness lines the trough may be an important feature because the more or less westerly wind behind it may in due course extend round the ridge which forms to south of the cut-off high. There was nevertheless no evidence that this more westerly flow is a feature of the cut-off mechanism.

Conditions for the formation of a cut-off high.—The main conditions favouring the formation of a cut-off high may therefore be summarized as follows:

(i) A jet stream from a southerly point is necessary.

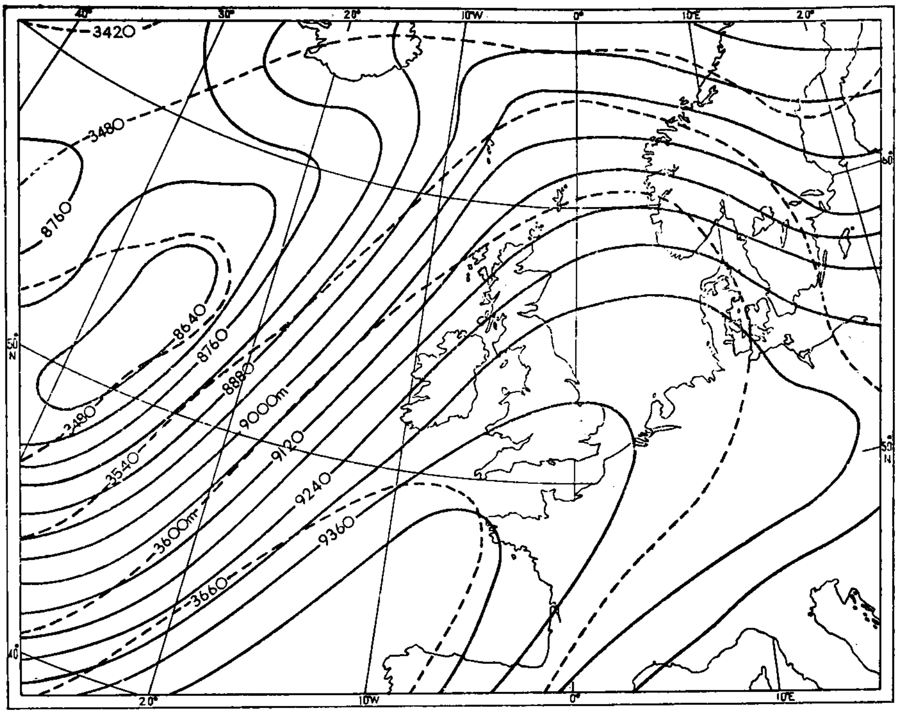
(ii) The amplitude of the ridge in the 500–300 mb thickness line through the jet should be at least 15° of latitude.

(iii) The jet should not veer with time and preferably should back ahead of an upper trough or low.

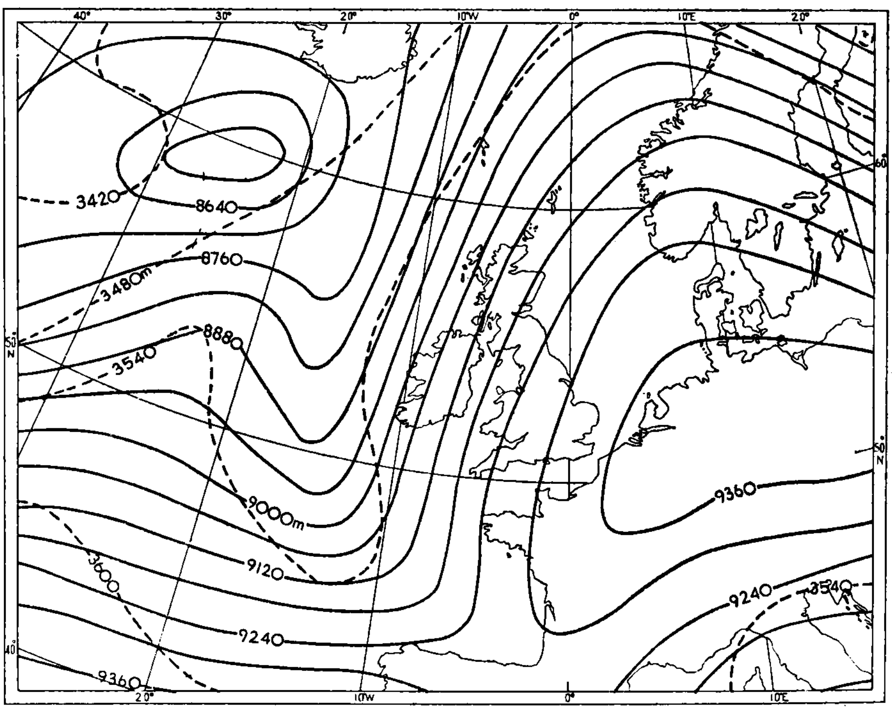
(iv) A thickness bulb should form around the peak of the thermal ridge, this giving 12–24 hours' warning of cut-off.

Typical example of the development of a cut-off high.—Figure 5(*a*), for 0000 GMT on 23 November 1959, shows a jet off Ireland which is backing ahead of the trough lying through the Azores. A thickness line just turns through 180° between the area off west Ireland and over south-west France, though a clearly defined bulb is not yet present. The amplitude of the thermal ridge is already about 22° of latitude and is likely to increase. Figure 5(*b*), the chart of 24 hours later, shows the jet backed by 20° and a cut-off high over north-west Germany.

Position and movement of the high.—A fairly good estimate of the initial latitude of a cut-off high was found to be given by the latitude of the centre of the thickness bulb 12 hours earlier. With jet directions around 140° the high was centred on the average 3° north of the thermal centre. With jet directions around 200° it was 3° south of this centre. On the other hand the difference in longitude between the two centres varied widely.



(*a*) 0000 GMT on 23 November 1959



(b) 0000 GMT on 24 November 1959

FIGURE 5—THE DEVELOPMENT OF A CUT-OFF HIGH

——— 300 mb contours   - - - - 500–300 mb thickness

(Closed 3600m thickness line inadvertently omitted over the high in 5(b))

In forecasting the movement of a high from one chart to the next the best method appeared to be to make use of the rough proportionality between the advective temperature change and the change of 300 mb height. Thus a high tends to move towards regions of 500–300 mb warm advection and away from regions of cold advection. In the initial stages, as the tongue of warm air spreads round the north side of the high, the average movement of the high was 80° veered from the direction of the jet, disregarding those highs whose movement was scarcely appreciable. Apart from one high which moved in a direction 50° backed from the jet, all moved in directions between 25° and 150° veered from it, and half of these directions lay between 70° and 100° veered. With the warm air continuing to overtake the high and advance to its north-east flank the track of the high usually showed a progressive veer with time. Only two highs, both of them retrogressive, moved to the left of the initial path.

Mean speeds of the highs throughout their life were measured. Of those with jets in the south-easterly group, one-third were nearly stationary and two-thirds averaged 200–250 nautical miles per day. Highs associated with south-south-westerly jets moved rather faster, the average speed being 300 nautical miles per day, only one in five remaining nearly stationary.

Half of the 45 highs lasted no more than 3 days, but a quarter of the total persisted as closed circulations for 5 to 10 days. None of the fast-moving highs remained a closed circulation for more than 3 or 4 days but otherwise no useful indication of the life of a high came to light. There was some proportionality between persistence and the number of closed contours but on the other hand some of the longest-lived highs maintained only one or two closed contours for most of the time. A forecasting rule based on the characteristics of a single system is not of course to be expected.

Cut-off lows at the 300 mb level.—Whereas a southerly jet is accompanied by the development of an upper ridge and perhaps a cut-off high, a jet from a northerly point is accompanied by a trough which usually extends southwards and develops a cut-off low provided the jet does not propagate forward to join a pre-existing low. The jet then bifurcates, one stream—usually the weaker—re-forming the trough in higher latitudes to north of the low. Since upper lows can develop in other ways, the starting point of the investigation was not the closed circulation (as in studying upper highs) but the northerly jet, the aim being to ascertain the circumstances in which it led to the formation of a cut-off low.

All jets over Europe and the eastern North Atlantic were examined for the months October to March from October 1959 to March 1963. As with highs, attention was confined to situations in which there were enough observations to establish whether a closed upper circulation developed near the jet exit.

Direction of the jet.—It soon became evident that northerly jets backed beyond 300° scarcely ever produced lows within 24 hours, so these directions were thereafter disregarded. The number of jets remaining was 50, of which 39 became associated with cut-off lows. Of the 11 jets which did not produce lows, 9 weakened by 20 or 30 knots, and it seems that this is a reliable indicator that cut-off will not take place however favourable the situation may appear in other respects.

From the method of selection of the jets most of the lows were necessarily over southern Europe or the Mediterranean: 34 lay between 30°N and 50°N and the remaining 5 to north of this zone. Nevertheless there was no evident relationship between the distribution and the topography.

Variations in the orientation of the jets were measured at various stages. If a jet was curved the direction was taken where the jet was furthest veered, provided the wind speed there was not appreciably below the peak speed on the axis. It was found that in the period from 24 to 12 hours before the formation of a cut-off low most jets veered, a few retained the same direction and none backed. The average 12-hour veer was 17°. In the period from 36 to 24 hours before cut-off the average veer was 9°. Even from 48 to 36 hours before cut-off there was backing of only 10 per cent of the jets. Thus provided a jet does not back (or weaken) with time, a cut-off low is likely to form sooner or later. The most significant indication of cutting-off is undoubtedly the direction of the jet, and Figure 6 shows the increasing probability of this development the more northerly the jet becomes, disregarding other factors.

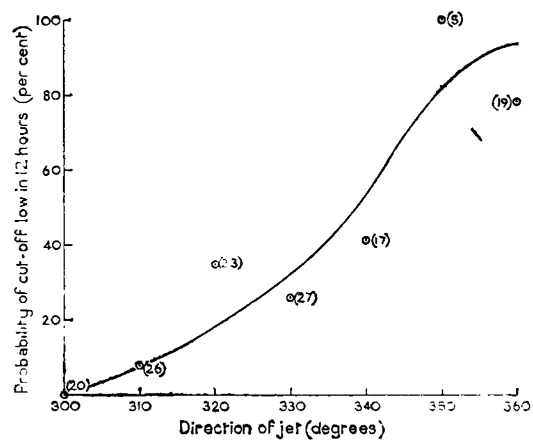


FIGURE 6—PROBABILITY OF CUT-OFF LOW IN RELATION TO JET DIRECTION

Number of occasions in brackets.

Amplitude of the thermal trough.—The veering of a jet is clearly accompanied on most occasions by increasing amplitude of the trough in the 300 mb contour lying along the jet axis, this amplitude being measured between the upwind ridge and the downwind trough. A linear relationship was found between the amplitude of the trough and the direction of the jet but, as was found with highs, amplitude gave only a rough indication of the imminence of cut-off. A low was cut-off within 12 hours only once when the amplitude was 10° of latitude or less.

Shape of the thickness lines.—An additional criterion was again provided by the shape of the 500–300 mb thickness lines. Whether the jet had propagated in such a way as to form a thickness bulb (as defined earlier for a ridge) at the base of the trough was found to be significant with jets between 320° and 340°.

Conditions for the formation of a cut-off low.—The complete rules suggested for forecasting a cut-off low are as follows:

(i) Cut-off is very unlikely within 12 hours if the amplitude of the trough in the 300 mb contour through the jet does not exceed 10° latitude.

(ii) Cut-off is very unlikely if the jet weakens by 20–30 knots.

(iii) A jet direction not further back than 310° is necessary for cut-off within 12 hours.

(iv) With a jet direction 300–310° there is
 (*a*) 75 per cent probability of no low in 24 hours or less
 (*b*) 5 per cent probability of a low in 12 hours.

(v) With a jet direction 320°–340° and no thickness bulb there is
 (*a*) 60 per cent probability of no low in 24 hours or less
 (*b*) 10 per cent probability of a low in 12 hours.

(vi) With a jet direction 320°–340° and a thickness bulb there is
 (*a*) 85 per cent probability of a low in 24 hours or sooner
 (*b*) 55 per cent probability of a low in 12 hours.

(vii) With a jet direction 350° or further veered, regardless of the existence of a thickness bulb, there is 80 per cent probability of a low in 12 hours.

Position and movement of the low.—Whereas the latitude of cut-off highs was fairly well related to the thickness bulb, the latitude of cut-off lows varied widely from it, and the narrower the 300 mb trough the more uncertain seemed the latitude of cut-off. On the other hand the longitude of the low was closely linked to that of the trough and averaged 4° longitude to east of the centre of the thickness bulb on the chart 12 hours before cut-off.

The directions of movement of the cut-off lows varied considerably from one system to another, depending to some extent on whether there was an associated surface depression and how strong it was. When there was already a surface system moving towards an easterly point, the upper low tended to move east or north of east. Nevertheless half the total number of 300 mb lows moved south-east into the sector 120°–140° during the first 24 hours. Meanwhile the base of the trough re-formed to north of the low and usually moved north of east, subsequently turning to east or south-east. 85 per cent of the lows moved a distance between 250 and 500 nautical miles in the first 24 hours, the average of them all being 350 nautical miles.

Half the lows persisted as closed circulations for no more than 2 days and only one-quarter of the total existed for more than 3 days. Three-quarters of the lows showed a net filling during the first 24 hours of life but there was no indication that the change in contour height over the centre was related to the life of the closed circulation.

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ASPECTS OF THE SYNOPTIC CLIMATOLOGY OF CENTRAL SOUTH ENGLAND

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Introduction.—Since the investigations of Abercromby,[1] much attention has been devoted to the description of pressure-map patterns over Europe[2] and over the British Isles.[3,4] Little attempt has been made, however, to determine in quantitative terms the resultant weather and synoptic climatology of characteristic pressure-patterns, despite the early study of local weather in selected areas of Britain in relation to 'weather types' by Sir Napier Shaw[5] and similar investigations for Cranwell.[6]

The present study attempts to provide more precise information of temperatures and rainfall in relation to pressure patterns for January and July, 1921–50, using the daily synoptic classification of H. H. Lamb[4] for the area of the British Isles. Daily averages of maximum and minimum temperature have been calculated for each type of pressure situation at ten stations in central south England, and averages of precipitation at twelve stations (Figure

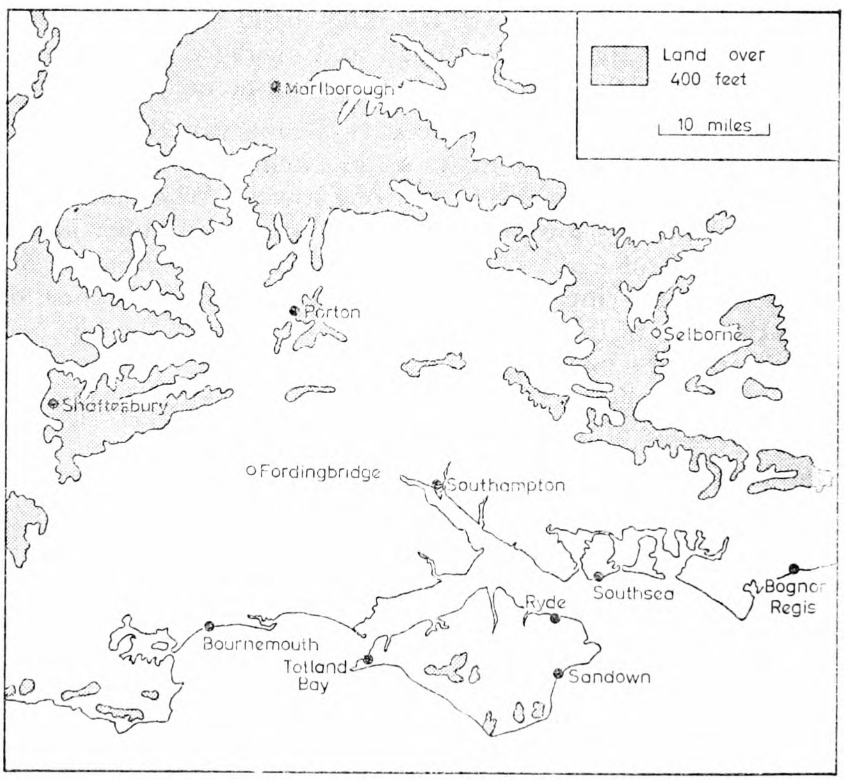

FIGURE I—LOCATION MAP OF STATIONS
• stations recording temperature and rainfall data
o stations recording rainfall data only.

1). In addition to these averages, standard deviations were also determined in each case, using the expression

$$\sqrt{\left\{ \left(n\Sigma x^2 - (\Sigma x)^2\right) \Big/ n(n-1) \right\}}$$

where Σ indicates summation of data, n is the number of terms and x data element. The work was performed on the *Pegasus* computer at the University of Southampton

Climatic conditions in January.—The results are set out in Table I, though synoptic types which accounted individually for fewer than 2½ per cent of the 930 days are omitted. Comparisons between stations are facilitated by the figures of departures of the calculated average temperatures for each type from the mean January values for 1921–50.[7] Complete descriptions of the type categories may be found in the paper by Lamb[4] and are not repeated here.

The *Westerly type*, which is the most common weather-map pattern (40 per cent frequency in January), brings relatively mild, changeable weather as depressions pass eastwards across the country. Moderate rainfall occurs with this type and the *Cyclonic westerly sub-type* (3 per cent frequency); 24-hour precipitation averages 2.5 to 3.4 mm over most of the region, although the higher figure at Selborne reflects orographic intensification over the western edge of the South Downs. Average daily maximum and minimum temperatures with Westerly flow are 1 to 2°C above mean January values at all stations. The high minima indicate a tendency for persistent cloud cover at night.

The *Cyclonic type* (12 per cent frequency) refers either to periods of very frequent depression passages across Britain or to a slow-moving low-pressure area lying over the whole country. Average minimum temperatures for Cyclonic type are about a degree above the mean minimum for January as a result of large cloud amounts, but average maxima are near the mean values (Table I). However, these averages may conceal high variability, arising from the changeable wind directions within depressions. For example, the standard deviation of the average maximum with Cyclonic type is between 2.5 and 3.3°C at ten stations, compared with 1.7 to 2.2°C for Westerly types, Cyclonic type is another major contributor to precipitation totals in January. since average daily falls are of the order of 4 mm. Similar high daily averages occur on days which are *Unclassifiable* (Table I), because these cases mainly represent complex synoptic situations with a depression affecting only part of the country.

North-westerly situations (4 per cent frequency) bring cold, generally unstable air across Britain when a northward extension of the Azores anticylcone causes depressions to approach from the north-west. Daily precipitation amounts average only 0.5 to 1.5 mm, although over high ground precipitation may take the form of snow showers. Average daily maxima and minima with North-westerly flow are close to the January averages at each station, with many occurrences of night air frost over high ground (Table I). Similar, but more extreme, conditions pertain to *Northerly* airflow when high pressure over the North Atlantic extends in a south to north wedge between 40° and 65°N, (3 per cent frequency in January). Average maxima with Northerly flow are 4 to 5°C at lowland stations and about 3°C on higher ground, whilst minima are −1 to 1°C and −2°C respectively. Despite the low day temperatures, little cloud cover is usually associated with Northerly flow and the winter sunshine provides some compensation for the cold air. Northerly flow is essentially unstable, but showers (not infrequently of snow) are only light over southern England due to the long passage of the air over land.

TABLE I—AVERAGES OF DAILY PRECIPITATION AND TEMPERATURES FOR TYPES OF AIRFLOW IN JANUARY (1921–50)

Type†		*NW*	*N*	*E*	*S*	*ACW*	*W*	*CW*	*C*	*AC*	*U*
Number of cases		35	32	49	105	23	372	28	110	96	43
Station	Height in feet					Precipitation *millimetres*					
Bognor Regis	24	0.8	0.8	2.7	2.8	0.3	2.9	2.6	4.0	0.6	4.0
Bournemouth (1)	139	1.3	0.7	2.1	4.2	0.7	2.8	2.7	4.1	0.7	4.5
Sandown	13	1.5	0.9	2.5	3.8	0.3	3.3	2.7	3.8	0.6	3.6
Ryde	13	1.0	0.7	2.7	3.7	0.6	3.3	2.9	4.0	0.5	3.6
Totland Bay (2)	140	1.1	0.5	2.5	4.1	0.8	3.1	2.6	4.3	0.7	3.8
Southsea (1)	7	1.1	0.6	2.4	3.4	0.3	2.9	2.5	3.9	0.6	3.7
Fordingbridge (3)	140	1.5	0.7	2.9	2.8	1.1	2.8	4.7	6.7	0.7	6.5
Southampton	65	1.0	0.6	2.4	3.8	0.5	3.3	3.4	4.2	0.6	3.9
Selborne	400	0.9	0.9	2.8	4.1	0.2	4.3	4.8	5.4	0.6	5.2
Porton	363	0.5	0.6	2.1	3.4	0.3	2.8	2.3	3.7	0.5	4.1
Shaftesbury	680	0.9	0.9	1.8	3.6	0.8	2.9	2.8	3.6	0.7	3.6
Marlborough	424	1.1	1.1	1.9	3.1	0.5	3.5	3.8	4.2	0.6	3.6
						Mean daily maximum temperature and departure from January average *degrees Celsius*					
Bognor Regis		7.6	4.7	4.1	7.3	7.7	9.1	9.4	7.8	4.7	5.9
		*0.2	−2.7	−3.3	−0.1	0.3	1.7	2.0	0.4	−2.7	−1.5*
Bournemouth		7.9	4.9	3.9	7.7	7.8	9.6	10.0	8.1	4.7	6.1
		*0.1	−2.9	−3.9	−0.1	0.0	1.8	2.2	0.3	−3.1	−1.7*
Sandown		8.1	4.7	4.4	8.0	7.9	9.8	10.2	8.5	5.2	6.6
		*0.0	−3.4	−3.7	−0.1	−0.2	1.7	2.1	0.4	−2.9	−1.5*
Ryde		7.8	4.7	4.2	7.9	7.3	9.7	10.2	8.3	4.7	6.1
		*−0.1	−3.2	−3.7	0.0	−0.6	1.8	2.3	0.4	−3.2	−1.8*
Totland Bay (2)		7.6	4.4	3.7	7.9	7.6	9.3	9.9	7.9	4.3	6.3
		*−0.1	−3.3	−4.0	0.2	−0.1	1.6	2.2	0.2	−3.4	−1.4
Southsea		7.9	4.7	4.3	7.7	7.5	9.4	10.0	8.3	5.1	6.1
		*0.0	−3.2	−3.6	−0.2	−0.4	1.5	2.1	0.4	−2.8	−1.8*
Southampton (4)		8.0	5.1	3.7	7.4	7.4	9.5	10.2	8.2	4.8	5.9
		*0.3	−2.6	−4.0	−0.3	−0.3	1.8	2.5	0.5	−2.9	−1.8*
Porton		6.8	3.5	2.6	6.7	6.8	8.9	9.3	7.1	3.8	4.8
		*−0.1	−3.4	−4.3	−0.2	−0.1	2.0	2.4	0.2	−3.1	−2.1
Shaftesbury		6.4	3.3	2.6	6.9	6.4	8.3	8.6	6.7	3.3	5.0
		*−0.2	−3.3	−4.0	0.3	−0.2	1.7	2.0	0.1	−3.3	−1.6*
Marlborough		7.2	3.3	2.5	6.5	6.9	8.8	9.2	6.9	3.4	4.6
		*0.4	−3.5	−4.3	−0.3	0.1	2.0	2.4	0.1	−3.4	−2.2*
						Mean daily minimum temperature and departure from January average *degrees Celsius*					
Bognor Regis		2.2	−0.3	−0.1	2.4	1.8	3.9	4.6	3.6	−0.2	1.3
		*−0.4	−2.9	−2.7	−0.2	−0.8	1.3	2.0	1.0	−2.8	−1.3*
Bournemouth		2.6	−0.4	−0.6	2.0	1.3	3.8	4.1	3.3	−1.2	1.3
		*0.4	−2.6	−2.8	−0.2	−0.9	1.6	1.9	1.1	−3.4	−0.9*
Sandown		3.1	0.2	0.6	3.3	2.3	4.3	4.7	3.8	0.3	2.1
		*0.0	−2.9	−2.5	0.2	−0.8	1.2	1.6	0.7	−2.8	−1.0*
Ryde		3.2	0.4	0.6	2.7	2.2	4.4	4.9	3.8	0.5	1.9
		*0.2	−2.6	−2.4	−0.3	−0.8	1.4	1.9	0.8	−2.5	−1.1*
Totland Bay (2)		3.1	0.4	0.0	2.7	2.0	4.4	5.3	3.8	−0.4	1.9
		*0.0	−2.7	−3.1	−0.4	−1.1	1.3	2.2	0.7	−3.5	−1.2*
Southsea		3.2	0.6	0.2	2.8	2.3	4.2	4.8	3.9	0.0	1.7
		*0.2	−2.4	−2.8	−0.2	−0.7	1.2	1.8	0.9	−3.0	−1.3*
Southampton (4)		2.1	−0.3	−1.0	2.1	0.5	3.4	3.8	3.0	−1.1	0.9
		*0.1	−2.3	−3.0	0.1	−1.5	1.4	1.8	1.0	−3.1	−1.1*
Porton		0.6	−2.3	−1.5	−0.1	−0.7	1.7	1.7	1.4	−2.7	−0.7
		*0.3	−2.6	−1.8	−0.4	−1.0	1.4	1.4	1.1	−3.0	−1.0*
Shaftesbury		0.8	−1.6	−2.0	1.2	1.3	2.8	2.6	1.6	−1.9	−0.3
		*−0.4	−2.8	−3.2	0.0	0.1	1.6	1.4	0.4	−3.1	−1.5*
Marlborough		0.6	−2.3	−1.7	−0.3	−0.9	1.8	2.2	1.3	−2.8	−0,8
		*0.2	−2.7	−2.1	−0.7	−1.3	1.4	1.8	0.9	−3.2	−1.2*

†*NW*=Northwesterly; *N*=Northerly; *E*=Easterly; *S*=Southerly; *ACW*=Anticyclonic westerly; *W*=Westerly; *CW*=Cyclonic westerly; *C*=Cyclonic; *AC*=Anticyclonic; *U*=Unclassifiable.
*Starred lines give the departure from average in both temperature tables. Notes: (1)1926–50 only; (2)1921–47 only; (3)Dockens 1922, 1927–47, 1949 and 1950; Cuckoo Hill (150 feet) 1921 and 1923–26; Furze Hill (150 feet) 1948; (4)No data for January 1941.

Easterly airflow has given rise to some memorable winters, but it is generally rather infrequent in January (8 per cent occurrence, including the Cyclonic easterly and Anticyclonic sub-types). Easterly spells usually develop with the establishment of a blocking anticyclone over Scandinavia, which may subsequently extend westwards. This situation can become persistent, as in the severe winter of 1947, and the conditions of January 1963 provide a further example. At Southampton, the temperatures in January 1963 fell considerably below the calculated average maximum of 3.7°C and the average minimum of −1.0°C for Easterly type (Table I), as Figure 2 shows. The hybrid

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PLATE I—SMALL MOTTLED WILLOW MOTH (LAPHYGMA EXIGUA)

See page 309

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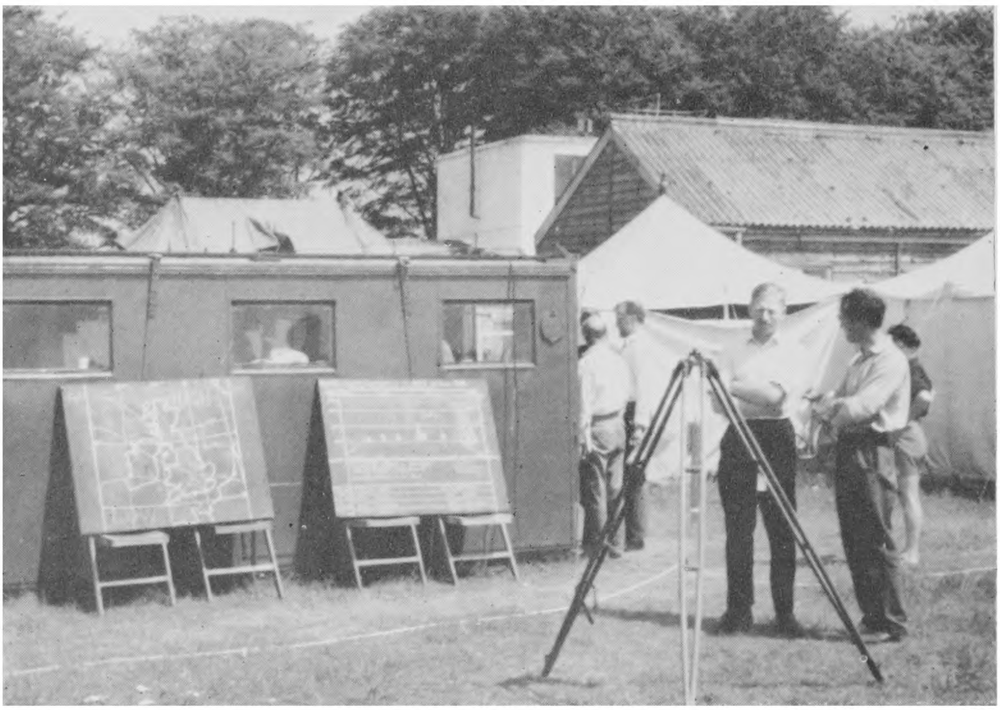
PLATE II—LIGHT TRAP USED BY ENTOMOLOGISTS

See page 309



Photograph by T. A. M. Bradbury

PLATE III—METEOROLOGICAL OFFICE UNIT AT THE NATIONAL GLIDING CHAMPIONSHIPS AT LASHAM FROM 25 MAY TO 3 JUNE 1963

See page 317

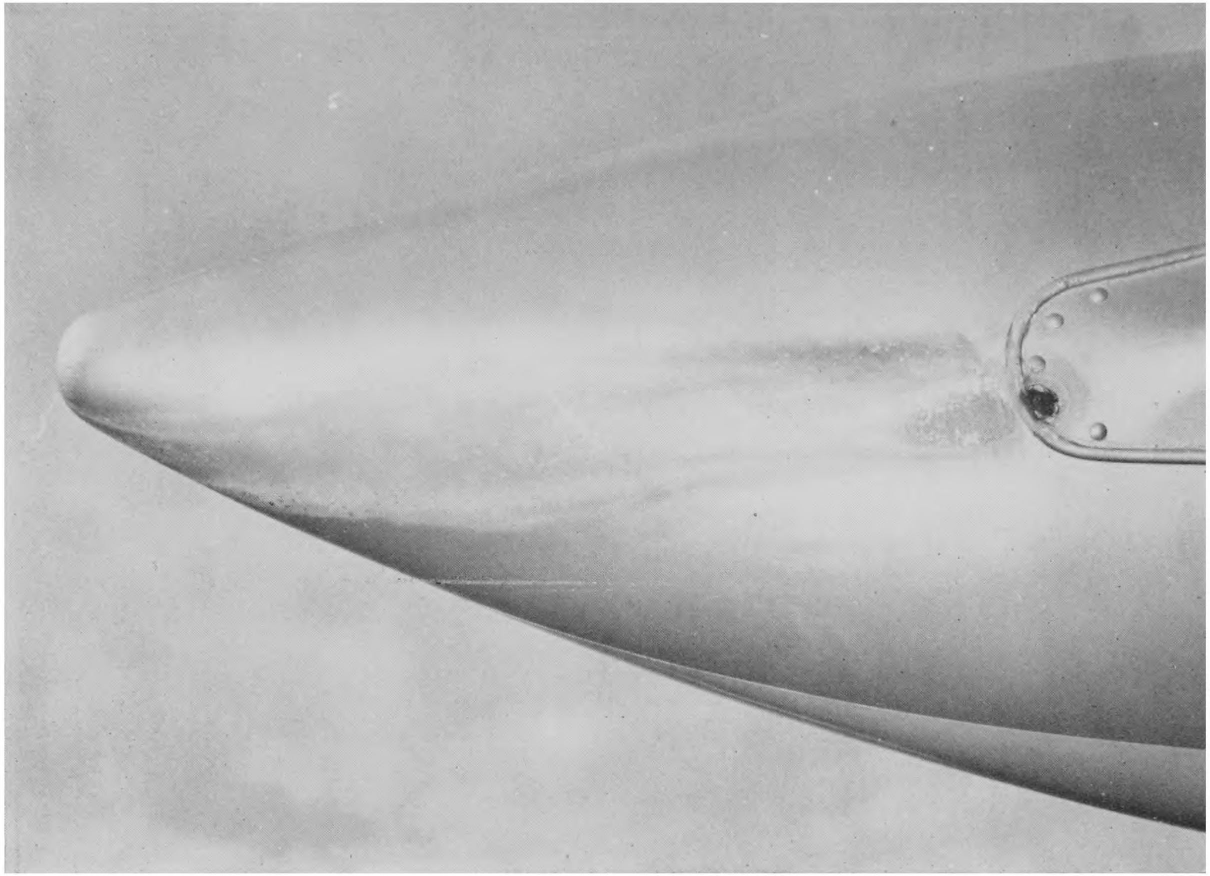


PLATE IV—DAMAGE CAUSED TO A JET PROVOST WING-TIP TANK BY LIGHTNING ON 3 APRIL 1963

The aircraft, based at RAF Cottesmore, was flying at 7000 feet in a cumulus-type cloud

To face p. 303

PLATE V—DISPLAY PANEL IN THE INFORMATION CENTRE AT THE ROYAL RADAR ESTABLISHMENT, MALVERN

On the occasion of the Open Days from 21 to 25 May 1963, (see page 317).

North-easterly and South-easterly types of January and February 1963 were not recorded during January 1921–50. Average daily precipitation over the area is about 2 mm with Easterly type, although on occasions moderate falls of snow may occur.

Cold weather in January occurs most frequently with the high pressure or *Anticyclonic type* (10 per cent frequency). Average maxima and minima for these cases are 3°C below the respective monthly averages, and night frosts are common, even at exposed coastal stations. The low averages of daily maxima reflect the development of frequent winter anticyclones in cold polar continental air from central or northern Europe, or in polar maritime air from the area between Greenland and the Faeroes. Precipitation falls occasionally on days which are classified as mainly Anticyclonic, but amounts are small (Table I).

Southerly flow (11 per cent frequency) is usually associated with anticyclonic blocking over Britain or the North Sea, or over central and northern Europe. The weather associated with this type cannot be readily specified, since a spell of Southerly flow may alternate either with Westerly or Easterly flow, giving rise to rather different conditions over southern England. Figure 2 provides an illustration of the latter case during February 1963. Thus,

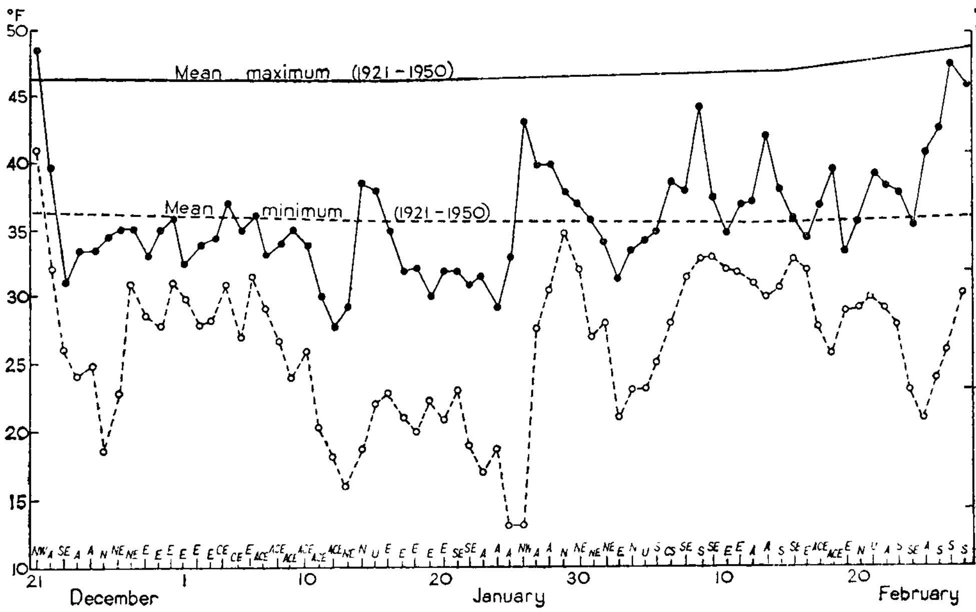


FIGURE 2—MAXIMUM AND MINIMUM TEMPERATURES AND TYPES OF AIRFLOW AT SOUTHAMPTON DURING THE WINTER 1962–63

• ——— • maximum temperatures   o – – – o minimum temperatures.

N=Northerly; *E*=Easterly; *S*=Southerly; *W*=Westerly; *NW*=North-westerly; *NE*=North-easterly; *SE*=South-easterly; *C*=Cyclonic; *A*=Anticyclonic; *CW*=Cyclonic westerly; *ACW*=Anticyclonic westerly; *CE*=Cyclonic easterly; *ACE*=Anticyclonic easterly; *CS*=Cyclonic southerly.

although the calculated temperatures are close to the averages for January (Table I), the values conceal considerable variability. Standard deviations of average maxima with Southerly type are 2.3 to 3.4°C. Average daily precipitation (generally rain) is 3 to 4 mm with Southerly flow.

While the averages of daily precipitation and daily maximum and minimum temperatures provide in general a useful indication of the climatic characteristics for particular types of synoptic pressure patterns, it must be recognized that non-characteristic conditions may be associated with any synoptic type over at least part of Britain. For example, January 1942 was much colder than average in central south England, despite the occurrence of 10 days of Westerly type during the month. The low temperatures were not related to any single flow-type and in fact were below average even on days of Westerly flow. Nevertheless, the very warm Januarys of 1921, 1932 and 1944 can be ascribed to an incidence of 20 or more days of Westerly type in each month. Temperatures at Southampton during January 1921 (Figure 3) were well above the monthly mean values on all except a few days. The very cold weather in central south England during the Januarys of 1929, 1940, 1941 and 1945 was associated with mixed spells of Northerly, Easterly, Anticyclonic and Southerly types, rather than with a single type.

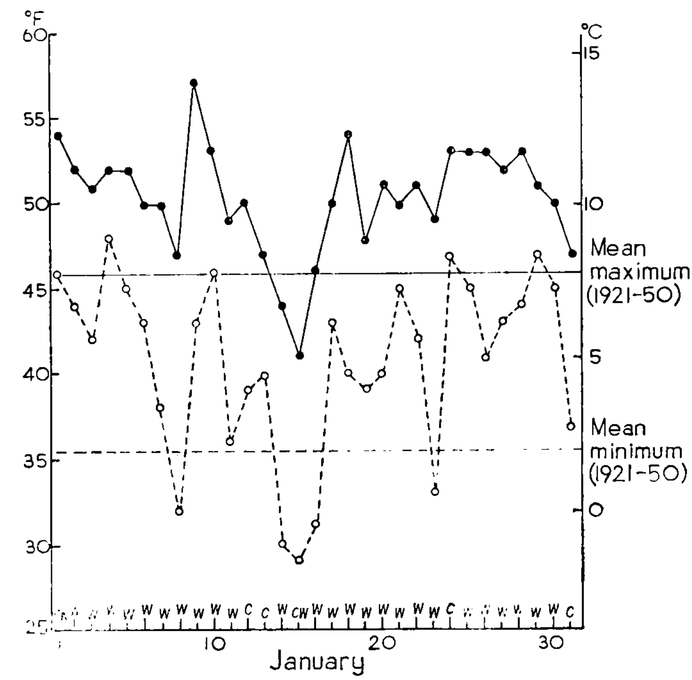


FIGURE 3—MAXIMUM AND MINIMUM TEMPERATURES AND TYPES OF AIRFLOW AT SOUTHAMPTON DURING JANUARY 1921

·———· maximum temperatures   o – – – o minimum temperatures.
C=Cyclonic; *W*=Westerly; *CW*=Cyclonic westerly.

The predominance of particular synoptic types in wet or dry months shows similar diversity. The area experienced above average precipitation in January 1936, 1939 and 1943, and each of these months had 8 or more days of Cyclonic type, though with spells of Westerly flow, and the Unclassifiable and Southerly types were also prominent. The extremely wet January of 1937, with 172 mm recorded at Southampton, had 17 days of Westerly type and 7 days of Southerly type. In contrast, Southampton received little precipitation in January 1949 and 1950, despite a high proportion of days with Westerly and Southerly flow, while Anticyclonic conditions were primarily responsible for the low precipitation in the area during January 1934.

Climatic conditions in July.—*Westerly type* (31 per cent frequency) is accompanied by below average maximum temperatures in July mainly as a result of its maritime origin, although cloud cover helps to keep the minima close to the mean monthly values (Table II). Rainfall may be widespread, but daily amounts average only a little over 1 mm. The *Cyclonic westerly sub-type* brings somewhat lower temperatures by day and precipitation averages of 1.5 to 3 mm. Although these values are less than in January, the amounts still provide an important contribution to summer rainfall totals. *Cyclonic type* situations, which are more frequent in July (19 per cent) than January, give similar maxima to those with the Cyclonic westerly sub-type (18 to 20°C). Average rainfall, some of which occurs with thunderstorms, is 3 to 4 mm at lowland stations and approximately 5 mm at Selborne, Shaftesbury and Marlborough, where orographic influence increases the amounts.

TABLE II—AVERAGES OF DAILY PRECIPITATION AND TEMPERATURES FOR TYPES OF AIRFLOW IN JULY (1921–50)

Types†		*NW*	*N*	*E*	*S*	*ACW*	*W*	*CW*	*C*	*AC*	*U*
Number of cases		52	39	26	43	37	293	46	176	137	48
Station	Height in feet					Precipitation *millimetres*					
Bognor Regis (1)	24	0.8	0.5	4.3	2.9	0.3	1.1	1.7	3.8	0.6	1.6
Bournemouth (2)	139	0.7	1.7	5.0	2.6	0.6	1.2	1.5	3.1	0.6	2.0
Sandown	13	1.1	0.6	5.2	2.8	0.5	1.3	1.9	3.8	0.6	1.7
Ryde	13	0.8	0.3	3.9	2.4	0.3	1.1	1.7	3.7	0.5	1.8
Totland Bay (3)	140	0.7	1.1	4.7	1.4	0.3	1.3	1.7	3.6	0.6	2.1
Southsea (2)	7	0.7	0.6	4.7	2.9	0.3	1.1	1.6	3.1	0.6	1.7
Fordingbridge	140	1.4	0.9	2.9	2.2	0.6	1.3	1.9	3.9	0.5	1.9
Southampton	65	1.1	0.7	2.8	2.7	0.9	1.1	2.0	4.4	0.6	1.1
Selborne	400	1.5	1.0	4.4	4.5	1.0	1.4	2.6	5.4	0.7	1.7
Porton	363	0.9	0.6	5.4	2.1	0.4	1.3	2.0	3.7	0.5	1.7
Shaftesbury	680	0.7	0.8	2.3	1.7	0.4	1.4	3.0	4.7	0.4	2.1
Marlborough	424	0.9	0.9	4.0	2.1	0.4	1.6	2.5	4.5	0.9	2.1

Mean daily maximum temperature and departure from July average
degrees Celsius

Station	*NW*	*N*	*E*	*S*	*ACW*	*W*	*CW*	*C*	*AC*	*U*
Bognor Regis (1)	19.3	18.1	20.6	20.1	21.6	19.7	18.4	18.7	21.6	20.6
	*−0.6	−1.8	0.7	0.2	1.7	−0.2	−1.5	−1.2	1.7	0.7*
Bournemouth	20.3	19.3	21.5	21.9	23.7	21.1	19.6	19.7	24.0	21.8
	*−1.1	−2.1	0.1	0.5	2.3	−0.3	−1.8	−1.7	2.6	0.4*
Sandown	19.9	18.9	21.0	20.7	22.6	20.4	19.3	19.3	22.1	20.7
	*−0.6	−1.6	0.5	0.2	2.1	−0.1	−0.8	−0.8	−1.6	0.2*
Ryde	20.1	19.1	21.2	21.8	23.4	20.9	19.7	19.7	22.9	21.3
	*−0.9	−1.9	0.2	0.8	2.4	−0.1	−1.3	−1.3	1.9	0.3*
Totland Bay (3)	19.3	18.5	20.8	21.1	21.8	19.2	18.1	18.6	22.1	20.1
	*−0.5	−1.3	1.0	1.3	2.0	−0.6	−1.7	−1.2	2.3	0.3*
Southsea (4)	20.1	18.8	22.2	22.2	23.3	21.1	20.0	20.0	23.5	21.7
	*−1.2	−2.5	0.9	0.9	2.0	−0.2	−1.3	−1.3	2.2	0.4*
Southampton (5)	20.2	19.2	22.6	22.9	23.9	21.2	19.6	19.8	24.4	21.6
	*−1.3	−2.3	1.1	1.4	2.4	−0.3	−1.9	−1.7	2.9	0.1*
Porton	19.4	18.6	21.6	22.9	23.8	21.1	19.6	19.7	24.3	21.8
	*−1.9	−2.7	0.3	1.6	2.5	−0.2	−1.7	−1.6	3.0	0.5*
Shaftesbury	18.4	17.6	20.1	21.4	22.7	19.6	17.8	18.3	23.2	20.3
	*−1.5	−2.3	0.2	1.5	2.8	−0.3	−2.1	−1.6	3.3	0.4*
Marlborough	19.4	18.3	21.7	22.9	23.8	20.7	19.4	19.4	24.7	21.6
	*−1.8	−2.9	0.5	1.7	2.6	−0.5	−1.8	−1.8	3.5	0.4*

Mean daily minimum temperature and departure from July average
degrees Celsius

Station	*NW*	*N*	*E*	*S*	*ACW*	*W*	*CW*	*C*	*AC*	*U*
Bognor Regis (1)	12.0	11.3	14.5	14.7	12.3	13.3	13.2	14.1	13.4	13.5
	*−1.4	−2.1	1.1	1.3	−1.1	−0.1	−0.2	0.7	0.0	0.1*
Bournemouth	11.6	10.8	13.6	13.6	11.4	12.7	12.6	13.2	12.4	12.7
	*−1.1	−1.9	0.9	0.9	−1.3	0.0	−0.1	0.5	−0.3	0.0*
Sandown	12.3	11.8	14.6	14.8	12.4	13.3	13.1	13.9	13.7	13.6
	*−1.1	−1.6	1.2	1.4	−1.0	−0.1	−0.3	0.5	0.3	0.2*
Ryde	12.9	12.1	14.7	14.4	13.2	13.5	13.1	13.7	14.0	13.7
	*−0.7	−1.5	1.1	0.8	−0.4	−0.1	−0.5	0.1	0.4	0.1*
Totland Bay (3)	12.4	12.0	13.7	13.9	11.7	13.2	13.1	13.3	12.7	13.3
	*−0.8	−1.2	0.5	0.7	−1.5	0.0	−0.1	0.1	−0.5	0.1*
Southsea (4)	12.7	11.9	14.8	15.0	12.8	13.9	13.4	14.2	14.1	14.1
	*−1.2	−2.0	0.9	1.1	−1.1	0.0	−0.5	0.3	0.2	0.2*
Southampton	11.4	10.7	14.1	13.9	11.6	12.7	12.3	13.3	12.8	12.7
	*−1.3	−2.0	1.4	1.2	−1.1	0.0	−0.4	0.6	0.1	0.0*
Porton	9.5	8.9	12.6	12.1	9.0	10.5	10.6	11.5	10.5	10.9
	*−1.2	−1.8	1.9	1.4	−1.7	−0.2	−0.1	0.8	−0.2	0.2*
Shaftesbury	10.3	9.6	12.1	12.2	11.2	11.3	10.8	11.5	12.1	11.2
	*−1.1	−1.8	0.7	0.8	−0.2	−0.1	−0.6	0.1	0.7	−0.2*
Marlborough	9.2	8.8	11.9	11.2	8.3	10.7	10.4	11.5	9.5	10.3
	*−1.2	−1.6	1.5	0.8	−2.1	0.3	0.0	1.1	−0.9	−0.1*

†See Table I for identification of types. *Starred lines give the departure from average in both temperature tables.
Notes: (1) No data for July 1923; (2) 1926–50 only; (3) 1921–47 only; (4) No data for July 1929; (5) No data for 1–23 July 1941.

North-westerly (6 per cent) and *Northerly* (4 per cent) situations are slightly more frequent in July than January. Each type of airflow brings relatively cool, showery weather, although in southern England falls are generally slight (Table II). Northerly type gives, on average, the lowest maxima and minima, which are 2 to 3°C and 2°C respectively below the mean values for July.

Easterly type is infrequent in July (3 per cent occurrence) largely as a result of the low frequency of blocking anticyclones over Europe.[8] Temperatures, especially minima, are above average when Easterly flow from the continent does occur in July. Daily rain amounts with Easterly flow in July average 3 to 5 mm, except further west at Shaftesbury; the rain tends to occur as thundery showers.

Southerly flow is also less frequent in July (5 per cent of days). Temperature conditions are almost identical with those for Easterly type, though rainfall is less. Average daily falls range from 1.5 to 3 mm, except where the orographic influence of the South Downs increases the figure to 4.5 mm at Selborne (Table II).

The highest average maxima in July occur with *Anticyclonic type* situations (15 per cent frequency) at all stations (except Ryde and Sandown); in some cases the average maxima are 3°C above the mean July maximum. Actual values are several degrees lower at coastal stations than inland, because of the development of sea breezes on many occasions,[9,10] Average minima with Anticyclonic type in July are close to the monthly mean minimum (Table II).

The *Unclassifiable* category accounts for 5 per cent of days in July, as in January, although a much smaller proportion of the month's precipitation falls on these days. Average temperatures are also closer to the monthly mean values (Table II).

The typical features of the synoptic patterns in July are not necessarily found every year (see also the discussion of January conditions). In July 1921 and July 1934 high average maximum temperatures and dry conditions were experienced at Southampton, and two-thirds of each month was dominated by Westerly and Anticyclonic types. Similarly, there were 18 and 20 days of Westerly flow during July 1923 and July 1933 respectively, occurring in long spells, and both were dry months with temperatures well above average at Southampton. The July minima in these latter cases were the two highest at Southampton during the period 1921–50. In July 1922, on the other hand, there were 15 days of Westerly type, 4 of the Cyclonic westerly sub-type and 7 days of Cyclonic type, but at Southampton the average daily maximum and minimum temperatures were well below average, and the rainfall total of 109 mm was the third highest for Southampton during 1921–50. The Westerly days in this month, however, did not constitute a long spell and the occurrence of a similar sequence in July 1936, again a very wet, cool month at Southampton, emphasizes the need to take into account not simply the total frequency of a type, but also the duration of particular spells and their relation to other synoptic types.

Significance tests.—Inspection of Tables I and II suggests that there may be no significant difference between the calculated averages for some of the sub-types, and even for major categories. In order to check this possibility, certain of the calculated type-averages have been tested in pairs by Student's t–test for temperatures at Southampton. The results for Southampton (Table III) show that, *of the pairs tested*, only Westerly and Anticyclonic westerly types are significantly different with respect to averages of maximum and minimum temperature in both months, and several pairs of types do not differ significantly for average maxima or minima. However, a complete analysis of the variance within and between the type categories, as suggested by Godske,[11] is desirable to clarify the present rather tentative results.

TABLE II.—SIGNIFICANCE LEVELS (PER CENT) FOR t-TE TS OF THE MEAN DAILY VALUES FOR TYPE CATEGORIES FOR SOUTHAMPTON

Types	Data	Maximum temperature	Minimum temperature
NW – N	January	0.1	0.5
	July	2.0	n.s.
N – E	January	n.s.	n.s.
	July	0.1	0 1
W – ACW	January	0.1	0.1
	July	0.1	0.5
W – CW	January	n.s.	n.s.
	July	0.1	n.s.
CW – C	January	0.1	n.s.
	July	n.s.	0.2
ACW – A	January	0.1	5.0
	July	n.s.	1.0
NW – S	January	n.s.	n.s.
	July	0.1	0.1
E – S	January	0.1	0.1
	July	n.s.	n.s.

n.s. = not significant, 5 per cent probability level adopted here.

Daily rainfall values possess a J-shaped distribution with the mode at zero and consequently the arithmetic mean is not a satisfactory statistic. The calculation of frequency distributions for rainfall amounts will be undertaken with a further computer programme in future. Nevertheless, the general comparability of averages for each airflow-type between the stations and the magnitude of the differences between the averages for the major type categories are sufficient to indicate the possible value of this approach.

More detailed information about rainfall amounts has been calculated for Southampton (Tables IV and V). The median and quartile values show that particularly marked differences exist between Northerly and Easterly

TABLE IV—MEDIANS AND QUARTILES OF DAILY PRECIPITATION (mm) AT SOUTHAMPTON FOR TYPE CATEGORIES (1921–50)

	NW	*N*	*E*	*S*	*ACW*	*W*	*CW*	*C*	*AC*
(*a*) January									
Upper quartile	0.6	0.5	2.3	6.8	0.3	2.2	3.7	6.4	0.0
Median	0.0	0.0	0.0	0.6	0.0	0.3	1.5	2.9	0.0
Lower quartile	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.8	0.0
(*b*) July									
Upper quartile	1.2	0.7	3.0	2.6	0.0	0.6	2.6	4.8	0.0
Median	0.0	0.0	1.2	0.3	0.0	0.0	0.3	1.5	0.0
Lower quartile	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE V—PERCENTAGE OF DAYS WITHOUT MEASURABLE RAINFALL AT SOUTHAMPTON FOR TYPE CATEGORIES (1921–1950)

	NW	*N*	*E*	*S*	*ACW*	*W*	*CW*	*C*	*AC*
January	57	72	53	38	61	47	18	19	82
July	58	67	38	46	81	63	41	30	88

types in July and between Westerly and Cyclonic westerly types, Westerly and Anticyclonic westerly types and North-westerly and Southerly types in January. The supplementary data of Table V also demonstrate that the number of rain days differs considerably for the Westerly sub-types and the Cyclonic type according to season.

It is intended to develop the investigations along the lines indicated above, as well as for other climatological parameters and other parts of Britain, with an extended computer programme. It is hoped that the availability of such data will help to complement the broader scale of research into climatic analogues carried out by the Meteorological Office and provide material of some assistance for extended-range forecasting.

Acknowledgements.—The author is indebted to the Director and Staff of the Computer Laboratory, University of Southampton for assistance with the writing and operating of the programme; to H. H. Lamb, Esq., Meteorological Office, for his encouragement and permission to use his classification; to Meteorological Office Archives for their help with the compilation of the data; and to his wife for punching and checking paper tape of the data.

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551.515.8:551.552:595.78

SMALL MOTTLED WILLOW MOTH IN SOUTHERN ENGLAND, 1962

By G. W. HURST

Introduction.—The agricultural branch of the Meteorological Office exists primarily to assist the agricultural community with problems in which meteorological factors come into play. Such problems are diversified, ranging from considerations of shelter in open country, some aspects of irrigation, ventilation and animal comfort, plant and animal diseases to pest control, etc. In these and many other directions positive help has been provided, but by their very nature many of the questions asked do not permit of very precise answers. From time to time, however, fairly exact questions are asked, and sometimes exact answers can be given; such a case was the arrival of the small mottled willow moth (*Laphygma exigua*) in 1962.

Many species of insect are not indigenous to this country but arrive here as immigrants in spring, or perhaps at other times when winds are favourable. The diamond-back moth in east Britain was a case where moths were traced back to west Russia (R. A. French and J. H. White),[1] and similar work in tracing spore back was done on black stem rust of wheat spore (W. H. Hogg).[2] Some insects, especially the more remotely based ones, are very variable in the regularity of their presence, and the small mottled willow moth (seen in Plate I) is a case in point. It has been thought worth-while to discuss the occasion of their arrival in May 1962 as it is very well documented, and illustrates the precision of tracking which is possible at times.

Entomological background.—The invasion by the small mottled willow moth took place on 6 May 1962 in southern England on a scale which has not been observed since records started in 1824. Nearly 1200 moths were counted from May to early November, with the highest individual total of around 100 at Brockenhurst, Hampshire, on 6 May; the previous highest annual count since at least 1930 was 300 in 1938, and in some years none were found.

Mr. R. A. French of Rothamsted, who has assembled these data, considered that the evidence was of arrival in the mid-evening of the 6th in south Hampshire, the Brockenhurst report suggesting a time of about 2100 GMT. Counts of these moths are governed by the existence of enthusiast c amateur entomologists, and the quite good network along southern England generally, strongly suggested west Hampshire as being the main arrival area, with fringe attack as far east and west as Kent and Cornwall. Subsequent catches were probably from the spreading out of the invasion of the 6th, either from the same batch, or with succeeding generations of these moths. There were relatively big catches too in Holland (the only other country in north-west Europe with a comparable observing network). The type of light trap in use is shown in Figure 1, and on Plate II is a photograph of an actual trap.

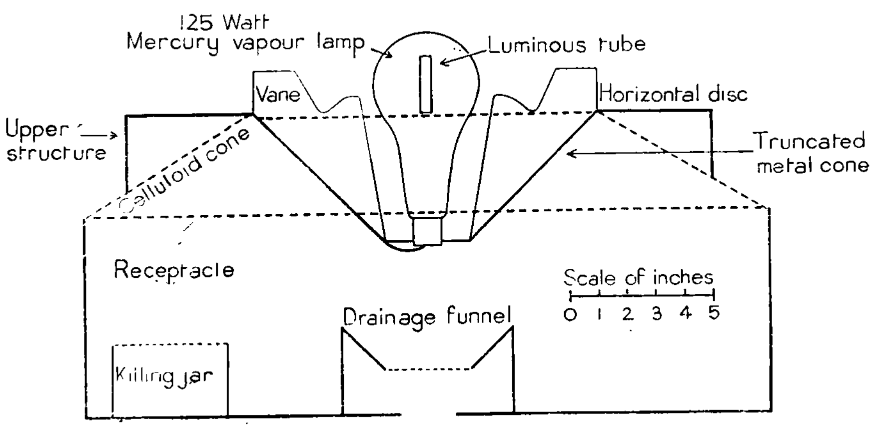

FIGURE I—DIAGRAMMATIC CROSS-SECTION OF LIGHT TRAP

Analysis.—The moths were believed by Mr. French to have originated from southern Spain or North Africa, and an approximate back-cast was made starting from south-west Hampshire at 2100 GMT, 6 May. This led back to somewhere west of the Straits of Gibraltar two days earlier, so examination was made of the wind and weather conditions in the area from Cape St. Vincent to Agadir. It was found that north-west Africa was the only place of departure, and the 2nd was the only time of departure reasonably in keeping with observations of wind and the general synoptic pattern. On that date a ridge extended from the south-west towards Spain, and east or north-east winds were blowing along much of the Moroccan coast on the afternoon of the 2nd. Insects such as moths are very much at the mercy of air currents and any altitude reached (above a relatively few feet) would be the result of vertical air motion. In fact, with the maximum temperatures which obtained on the 2nd, vertical currents to around 4000 feet could be expected from the Kenitra radiosonde ascent, so it is reasonable to envisage the moths leaving the African coast at that height. Insects can accept considerable pressure changes, and limitations on height are mainly imposed by temperature.

It will be noted from Figure 2 that the track passes near to both north-west

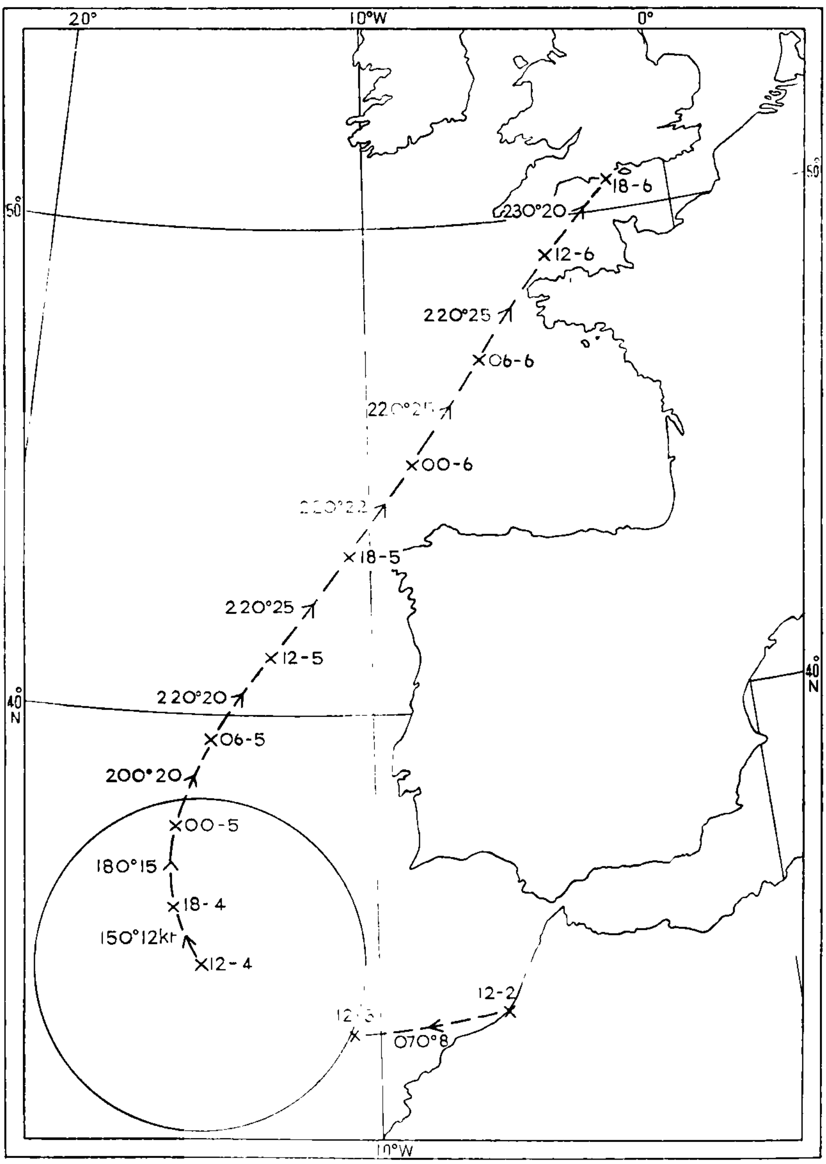

FIGURE 2—BACK-CAST OF FLIGHT OF LAPHYGMA EX.GUA 2–6 MAY 1962
x———x Flight track with time-date on right and wind directions and speeds (knots) on left.

France and north-west Spain, and the possibility cannot be disregarded on meteorological grounds that the moths came from one of these sources, though both are thought very unlikely entomologically. A further consideration militates against these possible sources, that of distribution in England. Had either of these places been the source, distribution in southern England would probably have taken the form of a maximum catch in some definite area, with abrupt fall-off to the west (fetching from off the departure coast), and a much less abrupt decline to the east, as the population in the north-west continent would have been assumed to spread out somewhat west to east; in fact, catches in Sussex and south Kent proved similar in the event to those in Devon and Cornwall. Departure from places well east of Brest or Corunna would vitiate this argument, but distances from the back-cast would become considerably greater.

Having determined departure date, place and height with fair accuracy, a back-cast was made from Hampshire, working on six-hourly intervals between main synoptic surface charts, and this is shown in Figure 2; the circle round the 1200 GMT, 4 May fix is an indication of the magnitude of possible error, taking 2 knots as the order of any such error. The assumption was made that there was a gradual fall of height throughout the flight from 4000 feet to the surface, and this may well not have been so; there was little in the way of ascending or descending air currents after the initial lift, so it may be that the moths relatively soon glided to near the surface, not much above the sea. The airstream was fairly homogeneous, however, and not much error would have been introduced if this did in fact occur. Trajectory winds were calculated from the isobars on the surface chart, with such support as was available from upper wind soundings.

The back track could not be continued beyond about 1200 GMT, 4 May with reasonable accuracy as winds by then were light and variable. However, by assuming departure from North Africa at midday on the 2nd, an estimated position was obtained for 1200 on the 3rd which would be within 200 miles of that obtained by back tracking from England. In this period of 24 hours from 1200 GMT, 3–4 May it is impossible to state winds with any conviction because of the uncertainty of the meteorological situation, and also the lack of data, but the further carry west-north-west of the moths seems very reasonable. The above casts assumed a northward contribution of about 2 knots from the moths as their migratory effort, and a rather bigger 24-hour gap would have existed without this assumption.

Flight as undertaken by the moths.—The exact source of the moths is not known, and meteorologically they could have started from almost any part of north-west Africa, as winds were rather variable. They probably left Morocco at or soon after midday on the 2nd, having been carried up to a height not exceeding about 4000 feet. Initially they were carried westwards on the southern flank of a ridge extending from the Canaries towards southern Spain and Portugal. Skies were well broken, and temperatures ranged from rather above 20°C at the surface to about 13°C at 4000 feet. By the 4th more pattern was obvious on the surface charts, and a small anticyclone in the Madeira area was moving east to north-east soon bringing the moths into a more southerly airstream, although still with clear weather. By the morning of the 5th, the anticyclone had reached Portugal, and the moths were now moving north-eastwards and soon became affected by the stronger south-westerly winds associated with the Atlantic depression and secondaries west and to the south-west of the British Isles. During the day the cloud increased fairly quickly, though its base was probably in excess of 2000 feet all day. Moth height by midnight was probably below 2000 feet assuming that moisture and blanketing of cloud were to be avoided. During the late afternoon the plotted track passed about 50 miles off Finisterre, and a landfall by at least some of the moths was likely, as the front of flight may well have been broad, with part of it crossing north-west Spain.

On the 6th, the relative humidity continued to rise as more definite cyclonic weather was approached, and across the Bay of Biscay the track moved into the warm sector of a depression west of Ireland, with a waving cold front towards the Azores. Cloud base fell quickly and by dawn the cloud base would probably have been a few hundred feet with patches of sea fog below. The track would just have missed Brittany in mid-morning. Some of the mass flight must, therefore, have crossed the north-west French coast and some doubtless landed; the low cloud and drizzle, however, may well have masked the ground below. Winds were of the order of 25 knots so that unless fairly low already, moths would probably have been swept across to the Channel as they were trying to descend.

The last leg of the flight was over a channel covered by low cloud with mist or fog patches present and light rain or drizzle in places. No doubt the moths were still descending and would probably be crossing at a low altitude, thus there were catches on the south coast of both Devon and Kent on the 6th. Temperatures were about 11–12°C with very humid air.

Catches were also made in Holland, with numbers of the order of 13 on 7 May and 7 on 8 May. These would be reasonably consistent with a continuation of the same trajectory for a further 12 hours or so; one isolated moth was caught on the 5th, but it may be that this was an incorrect identification as it is difficult to see how the mass invasion could have been beaten by 36 hours.

Conclusion.—The large numbers of small mottled willow moths found in southern England in the evening of 6 May 1962 are consistent with a departure of moths from the Morocco coast near or south of Rabat-Salé, some four days earlier. The track which was followed by the moths was almost entirely over the sea and remote from land; an opportunity of landing did exist for some members of the mass flight, and advantage of this was no doubt taken by many moths in landing in north-west Spain and north-west France. As far as others were concerned, however, their first landfall since sunny Morocco was the dull, drizzly south coast of England, and no doubt many regretted their flight.

Acknowledgements.—The author is grateful for the advice and information on entomological matters given by Dr. C. G. Johnson and Mr. R. A. French of Rothamsted.

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551.509.317:551.509.326

A FURTHER DEVELOPMENT OF THE INSTABILITY INDEX

By G. J. Jefferson, M.Sc.

In a previous article[1] an improved form of an instability index suggested originally by Rackliff [2] was described. The modified formula was:

$$T_J = 1.6\ \theta_{w900} - T_{500} - 11, \qquad \ldots \quad (1)$$

where θ_{w900} = the wet-bulb potential temperature at 900 mb and T_{500} = air temperature at 500 mb. This is an improvement on the original Rackliff formula since T_J depends only on the stability and not on the general temperature level of the air mass thus allowing its application to wider areas and all seasons. Tests have however suggested that further improvement is possible.

At London (Heathrow) Airport maps of the distribution of T_J have been drawn covering Europe and the Mediterranean. Experience has shown that while thunder has not occurred in areas where T_J is low, the occurrence of above threshold values by no means always coincides with an outbreak of thundery activity, especially in the Mediterranean. An examination of tephigrams from the areas concerned at once revealed the cause to be the presence of very dry air in the middle levels between 900 mb and 500 mb. An example of an ascent like this is shown for Palma, Majorca in Figure 1 where T_J = 32.

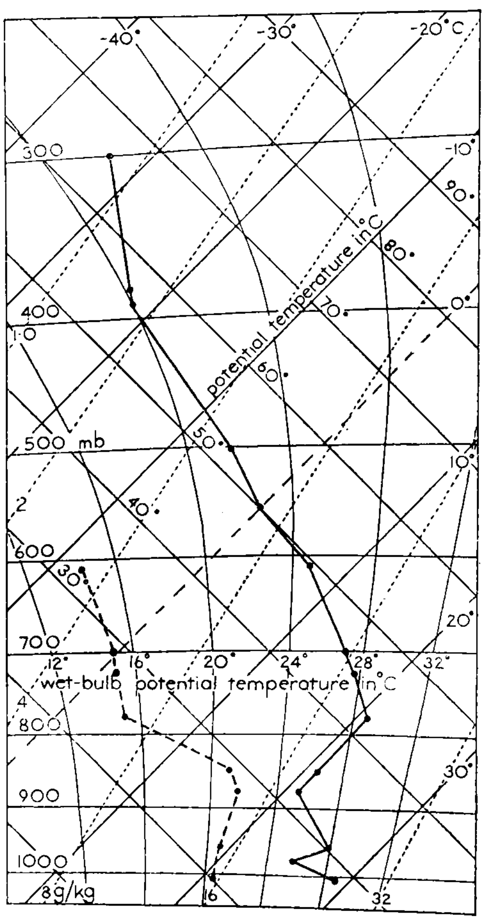

FIGURE 1—TEPHIGRAM FOR PALMA, MAJORCA, 1200 GMT, 11 JULY 1962

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

$T_J = 32,\ T_{mJ} = 27.5$

It was felt that it would be useful if the formula could be further modified to give an index which would allow for this so that a high value would always indicate a high probability of thunder. High-level thundery activity which is common in the Mediterranean area presents a different problem in forecasting from the air mass or frontal thunderstorms of northern and central Europe. The base of the thunder cloud (castellanus or high-level cumulonimbus) is often about 10,000 ft ($\simeq$ 700 mb). The humidity at the base of such a layer must be an important determining factor in the formation of convection cloud. Ideally, in this case, an instability index should be evaluated using θ_w for a level much higher than 900 mb. It would, of course, be difficult if not impossible to construct a map of isopleths of instability index to allow, in this way, for high-level convection in some places while still retaining θ_{w900} in others. Since convectional activity originating at lower levels is also seriously hindered by the entrainment of very dry air at levels above 900 mb, it is evident that the humidity of the air is an important factor in both cases. The 700 mb level, midway (in pressure) between the levels of the two parameters already in use, has been used to modify the formula as follows:

$$T_{mJ} = 1.6\ \theta_{w900} - T_{500} - \tfrac{1}{2}T_{d700} - 8, \quad \ldots \quad (2)$$

where the additional parameter T_{d700} is the dew-point depression in °C at 700 mb. Like the others, this is easily read from the tephigram. The factor of $\frac{1}{2}$ was introduced to avoid too heavy a weighting of the index by T_{d700}. It will be seen that this formula will give the same index as T_J when $T_{d700} = 6$°C. When the air at 700 mb approaches saturation, T_{mJ} will be increased a little (by a maximum of 3 for saturated air).

Some trials of this modified formula have been made and they show that areas of high T_J with no indication of thunderstorm activity are satisfactorily eliminated. The value of T_{mJ} for the Palma ascent in Figure 1 is $27\frac{1}{2}$, i.e. below the threshold value. No thunderstorms were recorded in the area as can be seen in Figure 2 which shows isopleths of T_{mJ} on that date as well as plots of thunderstorms. This example shows that areas of high T_{mJ} correspond quite well with area of thundery activity. Figure 3 is a recent example which shows isopleths of T_{mJ} for 1200 GMT and plots of thunderstorms for 1200 and 1500 GMT on 27 April 1963. The close correspondence between the two is again quite evident. It would appear that a threshold value of 28 or 29 is more satisfactory than 30 given by the previous formulae. T_{mJ} cannot be evaluated quite so quickly as T_J but is easily derived from it.

From equation (1) and (2)

$$T_{mJ} = T_J - (\tfrac{1}{2}T_{d700} - 3),$$

which leads to the following correction table for converting T_J to T_{mJ}:

T_{d700}	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
Correction to T_J	+3	+2	+1	0	−1	−2	−3	−4	−5	−6	−7	−8	−9	−10	−11	−12

In this way T_{mJ} can be obtained by using the table previously given for T_J.[1] When T_{mJ} has been plotted for all upper air stations for the area being considered, isopleths of 28 are drawn and these may be expected to show the limits of the area where thundery activity is likely at the time.

In using maps of T_{mJ} for forecasting, allowance must of course be made for advection. When a chart of T_{mJ} based on midnight ascents is used for forecasting the likelihood of thunder in the period of maximum activity in the following afternoon and evening, allowance can also be made for surface

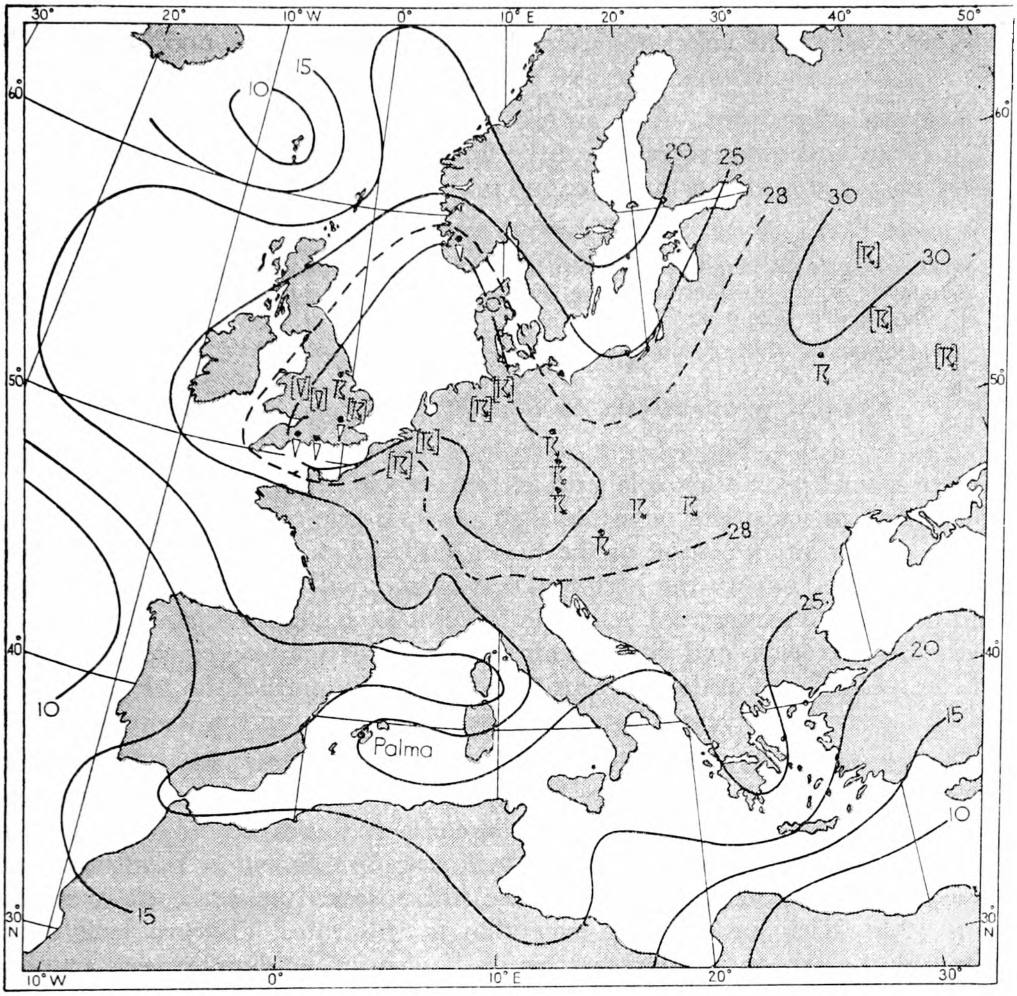

FIGURE 2—ISOPLETHS FOR T_{mJ}, 1200 GMT, 11 JULY 1962
Plots of showers and thunderstorms are for 1500 and 1800 GMT. Weather in the past hour is shown in brackets.

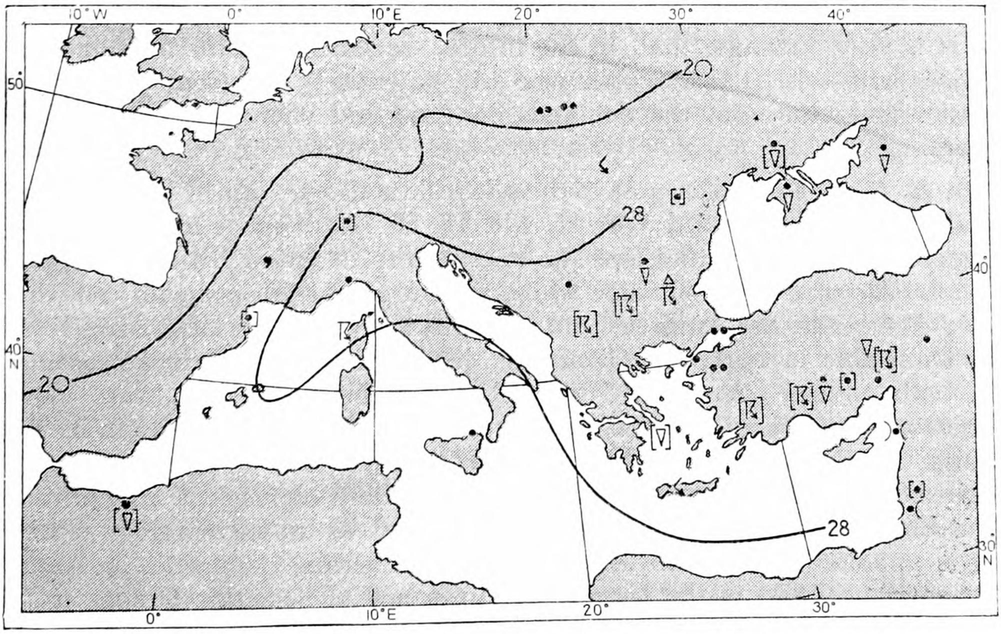

FIGURE 3—ISOPLETHS FOR T_{mJ} FOR 1200 GMT, 27 APRIL 1962
Plots of precipitation and thunderstorms are for 1200 and 1500 GMT. Weather in the past hour is shown in brackets.

heating. When the effect of surface heating extends above 900 mb the value of θ_{w900} will show some increases which in its turn will increase T_{mJ}.

Acknowledgement.—The author is indebted to Mr. B. Ramsey, Mr. D. T. J. Dean and other members of the forecast staff at Heathrow for their help in trying out this further modification on the forecast bench.

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NOTES AND NEWS

Special promotions to Senior Principal Scientific Officer

Mr. T. H. Kirk.—The scheme whereby a few scientists in the Civil Service receive special promotion solely on account of their individual merit and without regard to vacancies or established posts, is one of the more enlightened aspects of the organization of the Scientific Civil Service. His many friends both inside and outside the Meteorological Office will have heard with pleasure that the Interdepartmental Scientific Panel have recognized Mr. T. H. Kirk's merits in this way and have promoted him to Senior Principal Scientific Officer. On behalf of the Director-General and the staff of the Meteorological Office I offer our sincere congratulations to Mr. Kirk on this award.

During the whole of his career, except for a three-year period when he was engaged in marine meteorology, Mr. Kirk has been engaged on or concerned with forecasting duties. For most people such duties are so exacting that little or no time or energy is left to attack any of the scientific problems which have arisen in the day's work and are still unsolved after the day's work is done. Mr. Kirk has been an exception to this rule. The problems of the day-to-day work on the forecast bench have inspired him to seek practical solutions which can be applied in similar circumstances in the future. Both during the war and during the last six years he has been responsible for major forecasting units in the Mediterranean and has made full use of his opportunities to investigate forecasting problems peculiar to that area.

It is very fortunate that, in the future, we shall have the assistance of an officer with this particular flair who will be entirely free from administration duties and also from the demands on time and energy imposed by roster working.

A.C.B.

Mr. H. H. Lamb.—Like most of the scientific staff who joined the Meteorological Office before World War II, Mr. H. H. Lamb spent his early years on general forecasting duties and the opportunity to follow his natural bent for scholarship and research came when, after a period of duty with the whaling ship *Balaena* in the Antarctic, he joined the division for forecasting research at Dunstable in 1948. At Cambridge he had taken the Tripos examination in both natural sciences and geography and his work has always shown a flair for meteorology as a geographical science, that is geophysics in its proper sense. Building upon his *Balaena* experience he soon became a recognized British expert on the meteorology of the southern hemisphere in general and the Antarctic in particular and, in his capacity as the meteorology representative appointed by the Royal Society to the Scientific Committee on Antarctic Research (SCAR) of the International Council of Scientific Unions (ICSU), his special knowledge in this field is still valued. His main interest in more recent years has moved in another direction, to the variation of climate through the ages and especially during the recent historical period. Once more he has become a national figure in his chosen subject with many important published papers already to his credit and it is here that we expect his main work to lie for some time to come. Mr. Lamb is the kind of dedicated scientist for whom the scheme of promotion on special individual merit might well have been invented and we may be confident that he will repay with continuing scholarship of a high order. R.C.S.

Open Days at the Royal Radar Establishment, Malvern

The Royal Radar Establishment (RRE) at Malvern held a series of Open Days from 21–25 May 1963, the first that have been held since 1948. There were more than 2000 visiting scientists on the first four days, and an estimated 10,000 'families and friends' of the staff on the last day.

The Research Unit of the Meteorological Office at Malvern and the RRE group with which it is working on the application of radar techniques to meteorology, took an active part in the exhibits and demonstrations. A series of 30 display cards described the techniques used and some of the meteorological results obtained with a fixed 3 cm-wavelength Doppler radar and a high-resolution 8.6 mm pulsed radar. It was shown how the Doppler radar has been used to study the variation of drop-size distribution with height in steady rain, to determine vertical air motions within showers, and to measure small-scale variations of wind from the motion of precipitation particles in warm-front rain belts. The 8.6 mm radar has been used to study the fine structure in precipitation and clouds. Visitors were also shown a working display on a mobile 3 cm Doppler radar which is designed to extend the range of study to thunderstorms.

The Meteorological Research Unit also contributed a special exhibit to the main information centre in Nelson Hall at RRE. It consisted of a display panel, 30 feet in lenght, of the percipitation pattern through a cold front (see Plate V facing p. 303). W. G. HARPER

The Meteorological Office at the National Gliding Championships

During the period of the National Gliding Championships held at Lasham, Hampshire, from 25 May to 3 June 1963, a mobile meteorological office provided a forecasting service for the organizers and pilots (see Plate III).

One of the primary tasks of the meteorologists was to participate in task-setting each morning by providing the organisers with a detailed survey of the expected distribution of cloud, wind, and thermal conditions over the southern half of England, so that tasks for the eighty competing gliders could be chosen—tasks which would exploit the weather potential and test the skill of the pilots, yet which were neither too easy nor impossible. Detailed briefings of weather conditions over the selected routes were given at mass gatherings of pilots and crews each morning and discussions on the tactical use of the expected weather continued during the contest departures. Some glider pilots are now able to use conditions which a few years ago would have been regarded as prohibitive, and meteorologists have gained further insight into the structure and development of micro- and meso-scale weather systems.

J.F.

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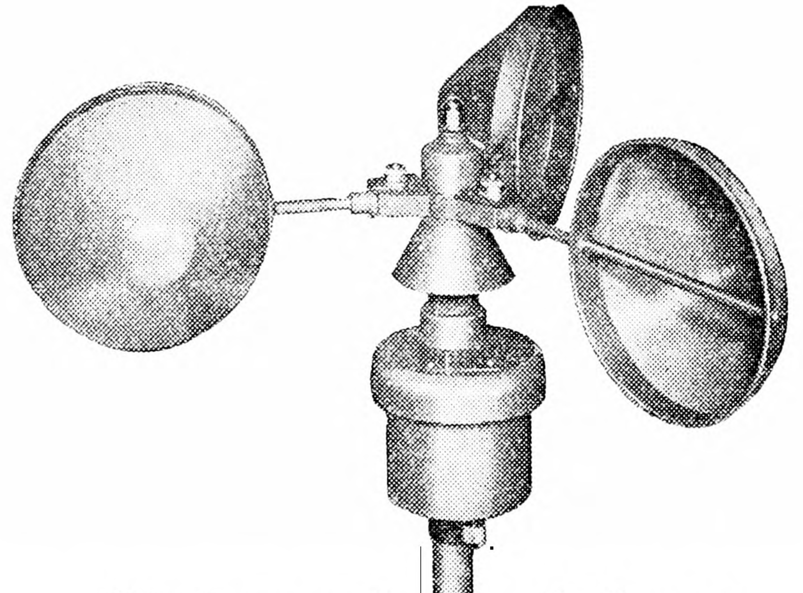

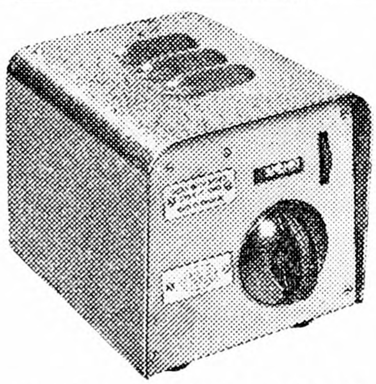

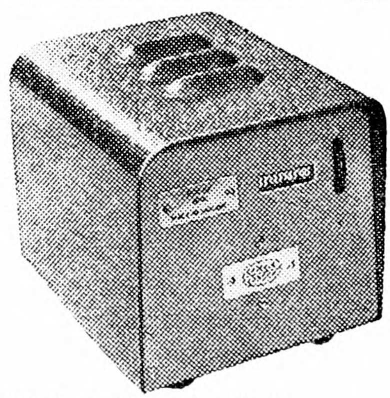

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JET STREAMS IN RELATION TO FRONTS AND THE FLOW AT LOW LEVELS

By C. J. BOYDEN

Summary.—Since surface observations are made more frequently and extensively than upper air observations, the accuracy of 300 mb charts, whether actual or forecast, is increased by making the fullest use of associations between jet streams and surface features. A brief examination of low-level winds beneath fairly strong jet streams is followed by a description of the jet-stream model at 300 mb in relation to fronts and surface circulations in different stages of development.

Introduction.—In 1947,[1] if not earlier, it was noted that a jet stream that could be associated with a frontal surface always lay on the warm side of it. Subsequently Palmén[2] stated that the jet stream was to be found nearly vertically above the intersection of the frontal surface and the 500 mb surface. This concentration of horizontal wind shear and correspondingly of horizontal temperature gradient, extending from the jet stream down to the surface front, suggested that the jet stream and the front were related dynamically, and the nature of the relationship has been studied by Sawyer.[3]

As was stated in the introductory paper,[4] we are concerned here with associations which are of practical forecasting use, regardless of whether the jet stream is the cause or the consequence of the feature with which it is associated. Forecasting by observed association is common practice since the forecaster's world is one in which observations are never as complete at any instant as he would wish. He is forced to infer from an observation in one place what is happening to another element elsewhere, the two places perhaps being separated vertically as well as horizontally. Before the last war his forecast of upper air flow was largely an inference from the surface pattern. Nowadays, with regular upper air observations and electronic computations, the primary forecast pattern is that of the middle troposphere and the surface pattern is made to conform to it. Nevertheless the jet stream is defined by lateral dimensions that are small in relation to the features of an upper air chart. It is smoothed in objective analysis—and often in subjective analysis—and still more so in a forecast chart, where it may even be impossible to locate the axis from the contours. It is therefore necessary for the forecaster to make what use he can of the surface analysis in locating the jet stream, and this paper deals with some empirical relationships between them.

The general association between jet streams and fronts.—Murray and Johnson[5] have given examples of the variability of jets in relation to fronts, but it is believed that more systematic relationships exist than seem to be implied by their examples.

A jet stream is intimately related to a strong baroclinic zone; a concentrated horizontal temperature gradient is the fundamental property of a front. Inevitably, therefore, a jet stream is associated with a front unless the front is thermally weak. An occlusion is an example of such a front, since by definition it lies outside a main thermal belt. Hence any relationship which appears to exist between a jet and an occlusion is almost certainly fortuitous. Such a jet is more likely to be associated with a secondary cold front behind the occlusion.

The wind at 300 mb is the resultant of the sea-level gradient wind and the intervening thermal wind. It is to be expected that relationships between the 300 mb wind and the surface fronts will show the greatest consistency in situations where the sea-level gradient wind is either relatively small or shows little variability. The investigation to be described was therefore restricted to occasions when the thermal wind component was most likely to dominate the 300 mb flow, so the selection was made using only the stronger jets. Occasions were first tabulated when any British radiosonde station reported a maximum wind of at least 130 knots (corresponding to a 300 mb wind of about 115 knots, the mid-point of the 'strong' category[4] used earlier). There were just over 400 such reports in the months October to March of 1960–61 and 1961–62.

The jets were classified according to the type of surface front with which they were associated. Of the 86 jets, 52 were ahead of warm fronts and 30 behind cold fronts; the remaining 4 could not be classified satisfactorily. None of these strong jets was associated with an occlusion. The distinction between warm- and cold-type jets was not always certain when the fronts and jets showed little lateral movement.

Warm-front jets in relation to the underlying 900-metre wind.—Comparisons were made between the 300 mb winds on or near the jets and the 900 m winds on the corresponding upper air ascents.

The 52 warm-front jets provided 273 pairs of observations. The directions of the jets ranged from 230° through north to 030°, 92 per cent of them lying between 260° and 360° and 64 per cent between 300° and 350°.

With jets in the sector from 300° to 350° the average backing of the 900m wind from the 300 mb wind was zero at 350°, 10° at 330° and 20° at 300°. Three-quarters of the 900m wind directions were within 20° of the direction given by this rule. The stronger the low-level wind the more commonly it conformed in direction, and differences exceeding 20° occurred mostly with 900m winds under 30 knots. Warm-front jets outside the sector 300° to 350° were associated with lighter and more variable 900m winds.

A result here which is of some forecasting importance is that when the direction of the warm-front jet is known to be at an angle of more than 20° to a surface geostrophic wind of 30 knots or more, the jet is unlikely to be a strong one. This is consistent with the well known weakening of a warm-front jet within the central area of a deepening surface depression.

Cold-front jets in relation to the underlying 900-metre wind.—In the same period there were 30 cold-front jets and a total of 124 pairs of observations on them. The directions of the jets lay entirely between 200° and 340°, 72 per cent of them being in the sector 240° to 300°.

There was greater uniformity than with warm-front jets in the directional relationship between 300 mb and 900m, the backing with height averaging less than 5° and with little systematic dependence on the direction of the jet. Ninety per cent of the 300 mb winds had a direction within 20° of that of the 900m wind.

Winds at 900m were markedly stronger than under warm-front jets, 90 per cent of the speeds being at least 30 knots. The lighter winds tended to veer more from the jets, being presumably at points towards the anticyclonic end of a cold front. Wind directions at 900m were between 230° and 330° in all but 2 of the 124 observations under cold-front jets.

The fact that a strong cold-front jet requires an accompanying surface geostrophic wind of at least 30 knots and little change of wind direction up to 300 mb is a useful safeguard against overestimation of the speed of the jet. Moreover, such conditions can rarely be satisfied except where the isobars are cyclonic.

The location of jet streams relative to warm fronts.—An attempt was next made to locate the jets relative to the pattern of fronts and isobars, using the same observations but without regard to whether the wind speed along the jet axis continued to exceed any particular figure. Starting from the British Isles a number of warm-front jets were tracked upwind on 300 mb charts until they passed over or near a surface front, however weak the flow may have become at some stage. The number of jets that could be followed satisfactorily was 44. It was noted that the position of many was related to the axis of the surface ridge ahead of the warm front, the mean position being 120 nautical miles (n.miles) beyond it (see Figure 1). The large majority of jets lay within little more than 100 n.miles of this mean position. On occasions when

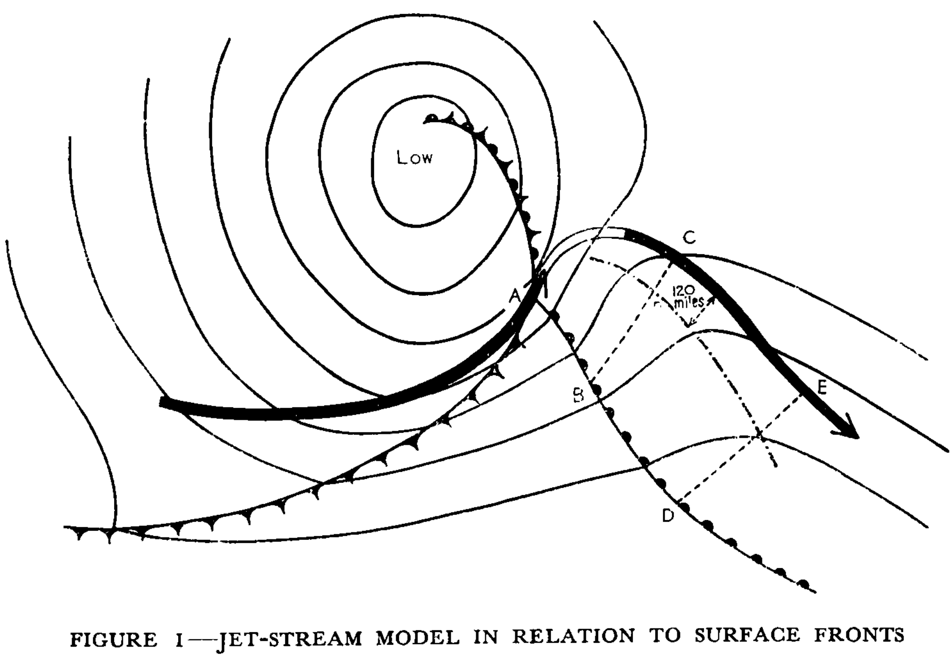


FIGURE 1—JET-STREAM MODEL IN RELATION TO SURFACE FRONTS

·——·——· Ridge line. The broad arrow represents the jet at 300 mb, the unshaded portion being a weak or broken jet.

the ridge axis became nearer the warm front at higher pressures it was found best to apply this 120-n.mile rule at the place where the axis was farthest from the front and draw the jet so that it approached no closer to the front at higher pressures (DE not less than BC in Figure 1). On occasions the rule failed through the jet being markedly backed from the ridge line, so every opportunity should be taken to obtain confirmation of direction from the thermal field. A few situations were also found when the ridge axis was not clearly defined on a single chart because the ridge travelling with the warm front had amalgamated with a pre-existing ridge: it is the former ridge which is associated with the jet. Finally the 120-n.mile rule is subject to modification towards the tip of the warm sector in a way that will next be described.

An essential characteristic of occlusion is that the major thermal belt, being the boundary to the warm sector, moves away from the primary surface depression. The jet moves laterally with it and hence the strong wind belt around a partly occluded warm sector is somewhat similar in shape to that around a warm sector in which occlusion has not begun. From a study of the 300 mb flow about 40 warm sectors, both with and without occlusion, it was found that the jet axis was on the average practically above the tip of the warm sector. This relationship was a fairly consistent one, though it should not be overlooked that the analyst takes into account a relationship of this kind when drawing the charts. It was further noted that the direction of the strongest wind at 300 mb was the same as that of the underlying sea-level isobars in the warm sector.

The majority of strong jets over the British Isles ahead of warm fronts were found to lie between 300 and 450 n. miles from the front, this distance being measured perpendicular to the jet (BC in Figure 1). The larger distances were found when the front was slow moving but there were a number of exceptions. The relationship between the distance from the front and the distance from the tip of the warm sector (BC to AB in Figure 1) was also a variable one but it appeared that the average distance was fairly constant until AB reduced to a distance equal to 7° latitude, from which stage the line of the jet turned in towards the tip of the warm sector.

From the relationship with the ridge, the direction and position of the jet over the tip of the warm sector and from the 7° relationship we have a first approximation to the position of the warm-front jet for use when upper air information is scanty.

The location of jet streams relative to cold fronts.—The strong cold-front jet is linked at each end to a warm-front jet or axis of strong wind, and in addition the direction of the jet near the tip of the warm sector is known. The tendency of the jet to cut surface isobars at a very small angle is a further aid in locating it. It was also found that the majority of strong cold-front jets were at a distance behind the front which was proportional to the distance from the tip of the warm sector, the separation being increased by 140 n.miles, on the average, for each 10° latitude distance. A minority of jets departed far from this relationship.

Jet speed in relation to the low-level pattern.—As yet no mention has been made of the variations of speed except to imply that the relationships between the jet and other features described above do not necessarily hold for weaker jets. Without adequate upper air information it does not seem possible to estimate the strength of a jet but the low-level pattern gives an indication of the relative speeds along a jet. The statistics given above as to the sectors in which strong jets are found and the relationships with low-level winds indicate at least the circumstances in which a strong jet is not to be expected. It is of interest to contrast the situation over a depression possessing a small circulation with that existing when a depression is in a later stage of development. The former is illustrated by the charts of 0000 GMT on 20 January 1962 (Figure 2) when a strong warm-front jet existed over Scotland and there was no opposing sea-level gradient wind. The cold-front jet, favoured by supporting low-level

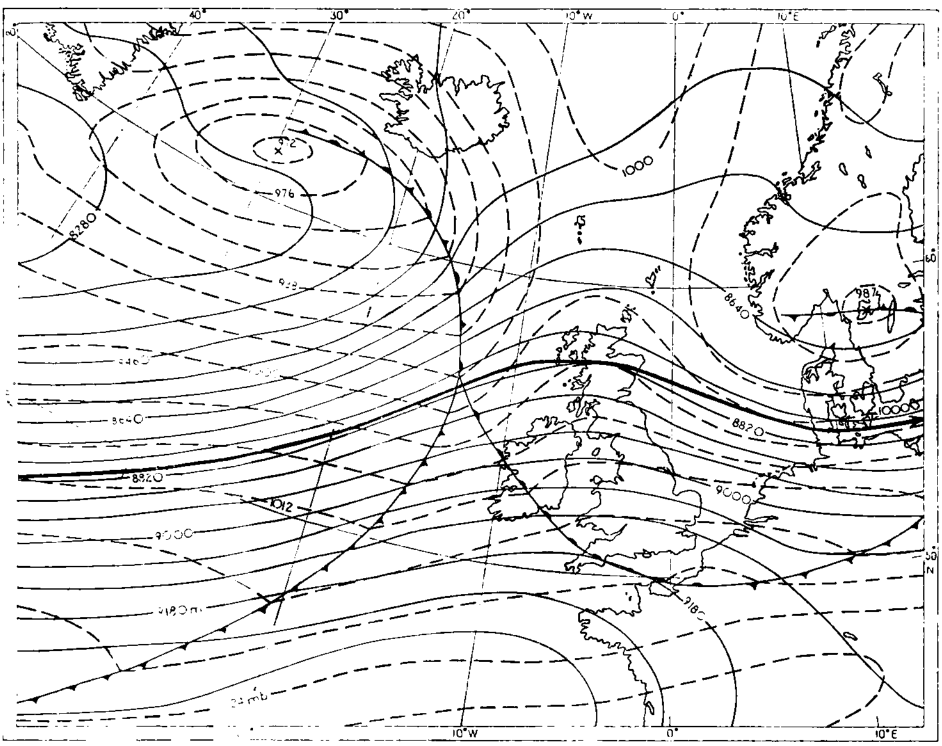


FIGURE 2—WARM-FRONT JET CONTINUOUS WITH THE UPSTREAM COLD-FRONT JET AT 0000 GMT, ON 20 JANUARY 1962

——— 300 mb contours, - - - - surface isobars. The broad arrow shows the position of the jet.

winds of over 40 knots, extended to join the warm-front jet in a continouus flow around the frontal system. Essentially the strong unbroken jet resulted from the absence of a surface pattern which would have given meridional advection of thickness lines. A different pattern is that of 1200 GMT on 31 January 1960 (Figure 3). Over this depression the surface flow around the warm sector was more meridional and there was consequently a greater amplitude in the 300 mb flow. The strong cold-front jet weakened or broke over the upper ridge and strengthened again to become a strong warm-front jet east of Denmark. In general the weakening between a cold-front jet and a warm-front jet is more pronounced the greater the direction change between them. Large curvature in the upper ridge imposes a limiting speed since the negative relative vorticity cannot exceed the Coriolis parameter for any length of time.

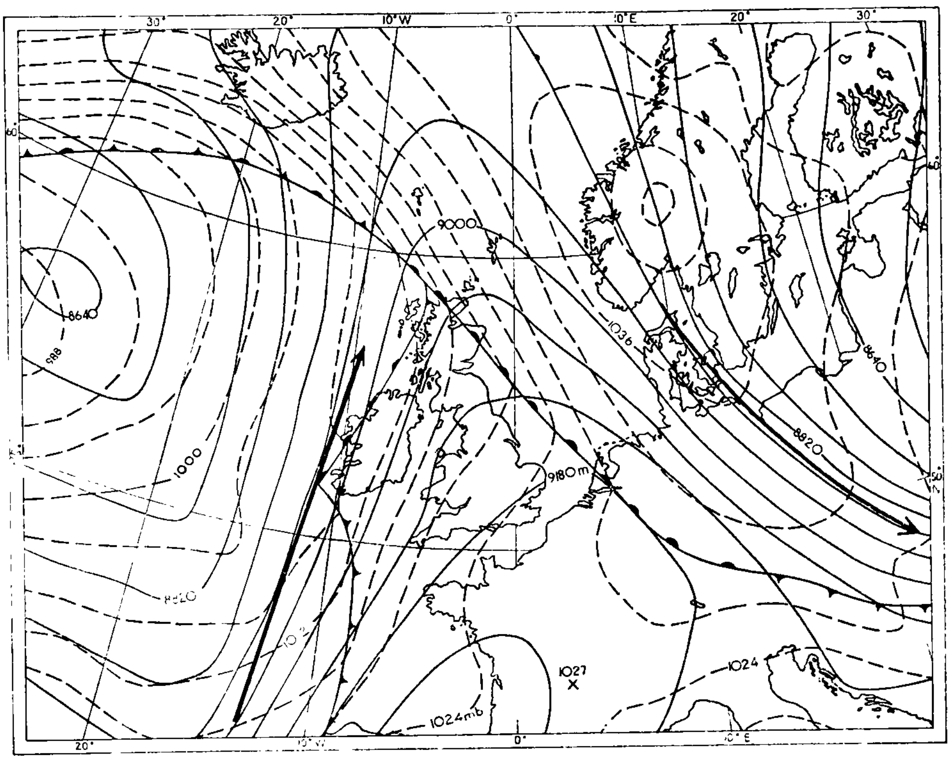


FIGURE 3—WARM-FRONT JET SEPARATED FROM THE UPSTREAM COLD-FRONT JET AT 1200 GMT, ON 31 JANUARY 1960

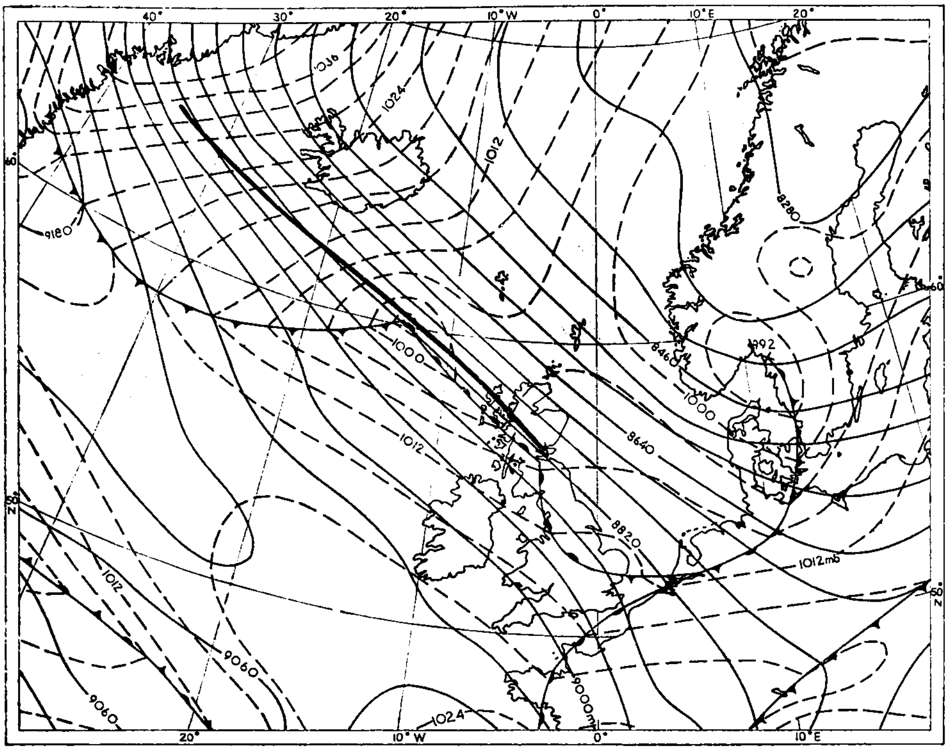
——— 300 mb contours, - - - - surface isobars. Broad arrows show the position of the jets.

Changes in the orientation of a jet.—Since the jet is a feature of a change to a more meridional flow the jets themselves must become more meridional, at least in the earlier stages of development. Thus a cold-front jet, formed by cold advection on the east side of an upper trough, should back with time, and a warm-front jet, on the east side of an upper ridge, should veer. More loosely it can be said that north-westerly jets tend to veer and south-westerly ones to back, but it must be remembered that, particularly when the wave-train itself is turned from the west–east direction, the character of a jet is not defined by its direction. Figures 4(*a*) and (*b*) depict a north-westerly jet which was mainly of cold-front type and therefore backed as cold air moved further south over the Atlantic than over Scotland.

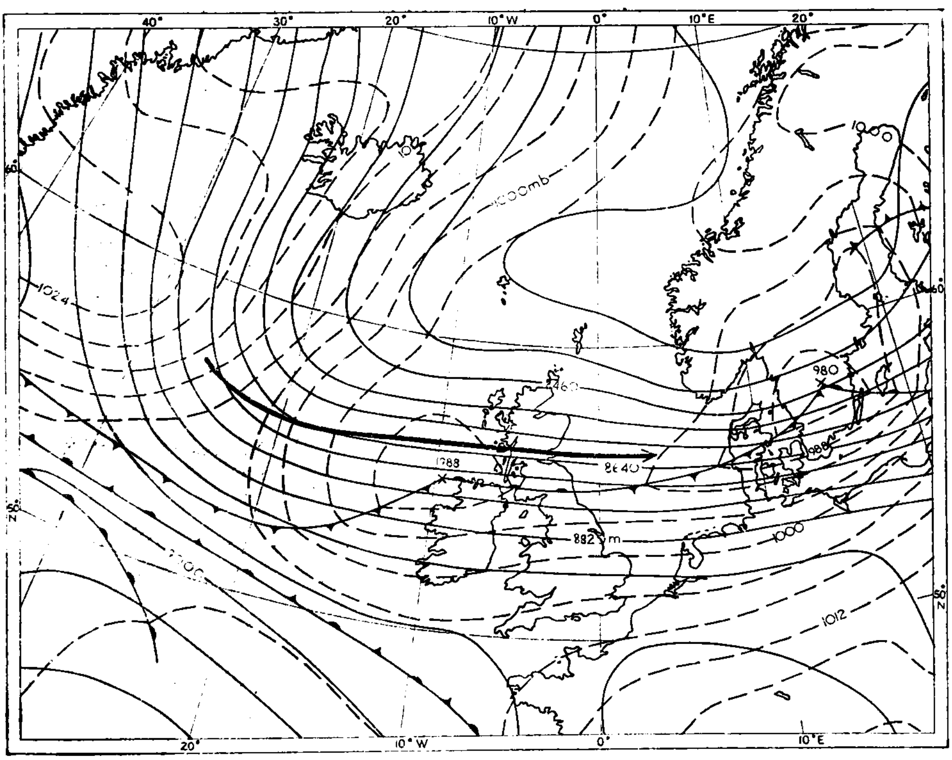
Warm-front jets.—The large majority of warm-front jets are from a north-westerly point and, like the associated front, either veer or maintain their direction in a manner which is not unduly difficult to forecast by the method of thickness advection. Following perhaps two or three days of veer at an average rate of 20° per 24 hours the ultimate development is likely to be one of the following, of which (ii) occurs most frequently:

(i) The jet shortens and weakens as the upwind ridge draws closer to the downwind trough. This is usually accompanied by a backing of the jet.

(ii) A cut-off low forms and the jet gradually propagates forward round the east side of the low.



(*a*) 0000 GMT, on 18 January 1960

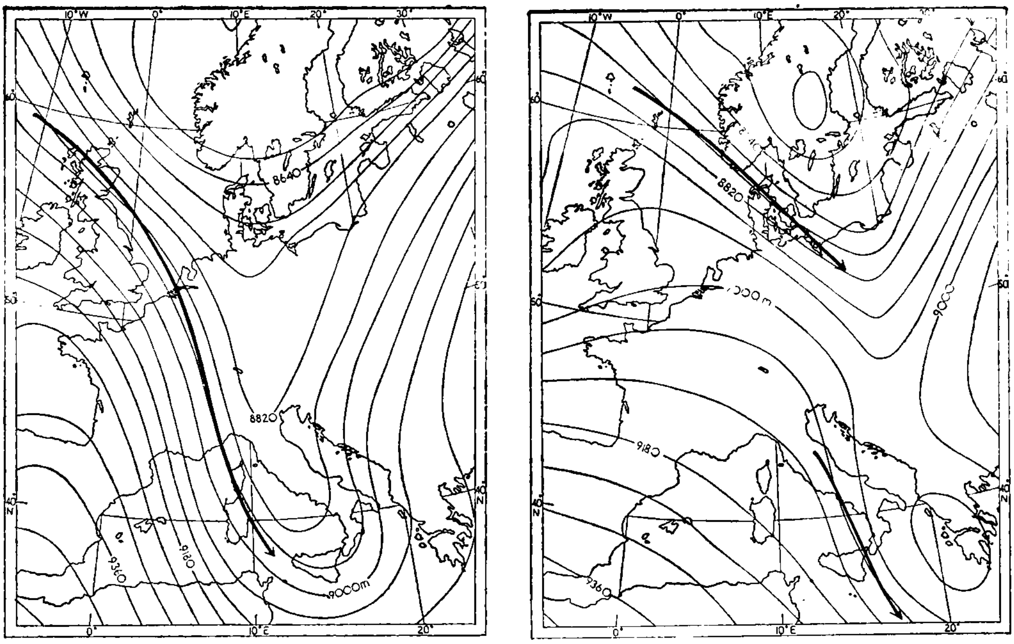


(*b*) 0000 GMT, on 19 January 1960

FIGURE 4—SEQUENCE SHOWING MARKED BACKING OF A NORTH-WESTERLY JET

———— 300 mb contours, - - - - surface isobars. Broad arrows show the position of the jets.

(iii) A cut-off low forms and the jet divides as shown in Figures 5(*a*) and (*b*), one part of the jet rounding the low, as in (ii) above, and the other part forming the western limb of the new trough, backing as it moves east.



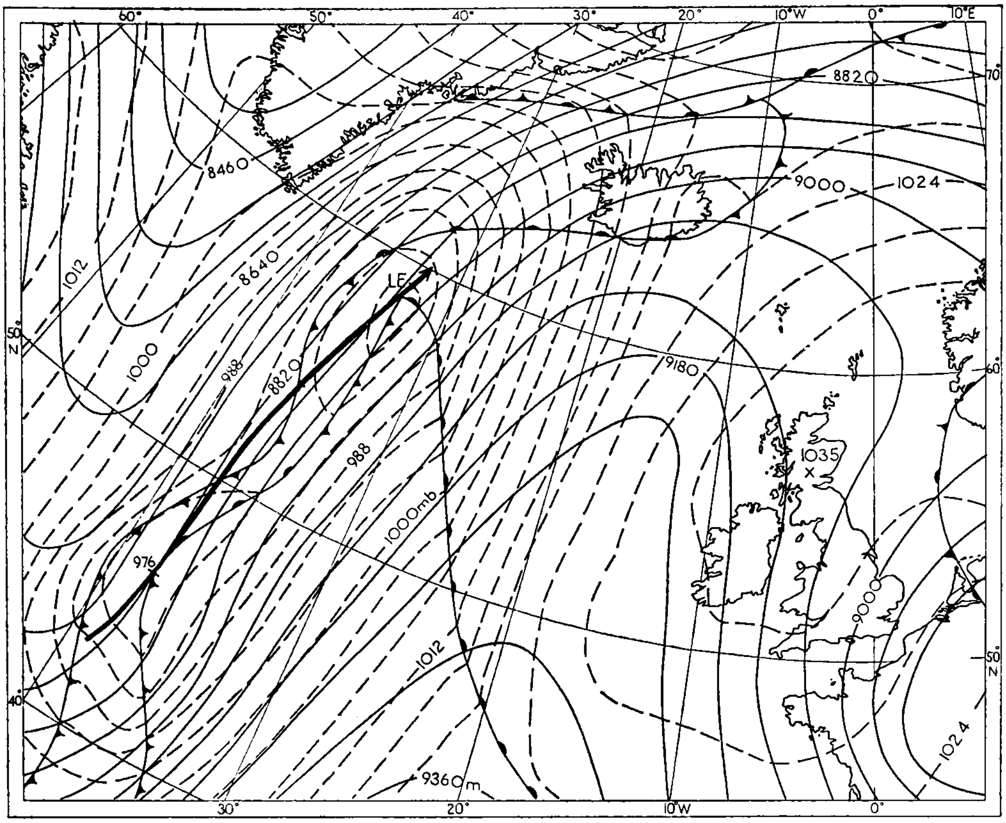
(*a*) 1200 GMT, on 7 December 1961 (*b*) 1200 GMT, on 8 December 1961

FIGURE 5—SEQUENCE SHOWING THE BREAKING OF A JET ON FORMATION OF A CUT-OFF LOW, WITH BACKING OF THE NORTHERN SECTION

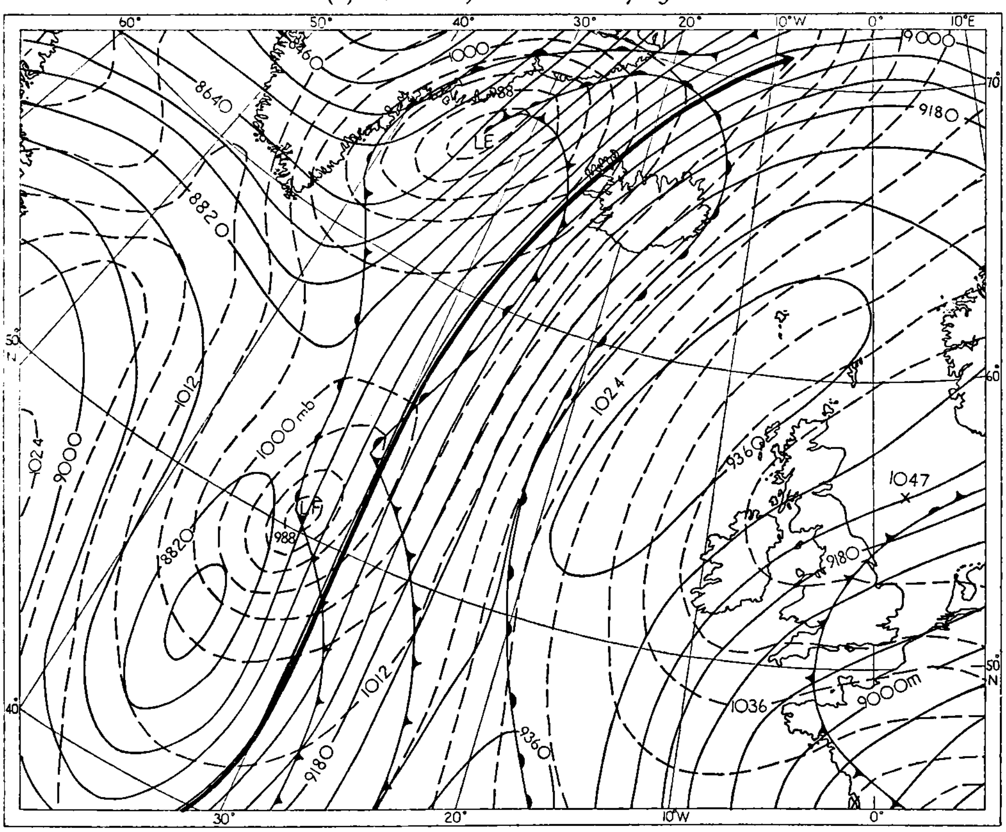
———— 300 mb contours. Broad arrows show the position of the jets.

It is not possible to be as specific in regard to the curved part of the warm-front jet which is linked to an upwind cold-front jet (see Figure 2). It is difficult to specify a direction for such a jet, so the terms 'veering' and 'backing' have little meaning. On most of these occasions there are no major systems below the jet and the upper ridge probably moves very slowly east with little change of shape, so over a fixed point the jet tends to back slowly. However, each situation is best considered individually in terms of thickness advection.

Cold-front jets.—A cold-front jet usually has cyclonic curvature over a considerable distance and often merges with an upwind warm-front jet. It is broadly true that the cold-front jet backs with time, the sharpening of the trough between the two jets eventually being relieved by the formation of a cut-off low. Nevertheless the backing of the cold jet is often intermittent and local because it lies over the region where cyclogenesis is most likely to occur. The formation of a surface depression under the eastern limb of an upper trough increases the eastward movement of the thickness lines to the south of it, and thus of the jet. The north-eastward movement of this low induces a travelling wave in the jet which normally increases the net eastward movement of the jet. Whether the jet is finally backed or veered from its earlier orientation depends on the rate of development of the depression relative to its speed along the jet. On many occasions, if not most, the jet extends north-east behind the depression but remains fairly straight. On the other hand Figure 6 shows how large deepening can cause a jet to veer and break. At 1200 GMT on 6 February 1960, low 'LE' was moving north-east (Figure 6(*a*)) and 24 hours later (Figure 6(*b*)) the jet (essentially of cold-front type) had extended beyond Iceland with



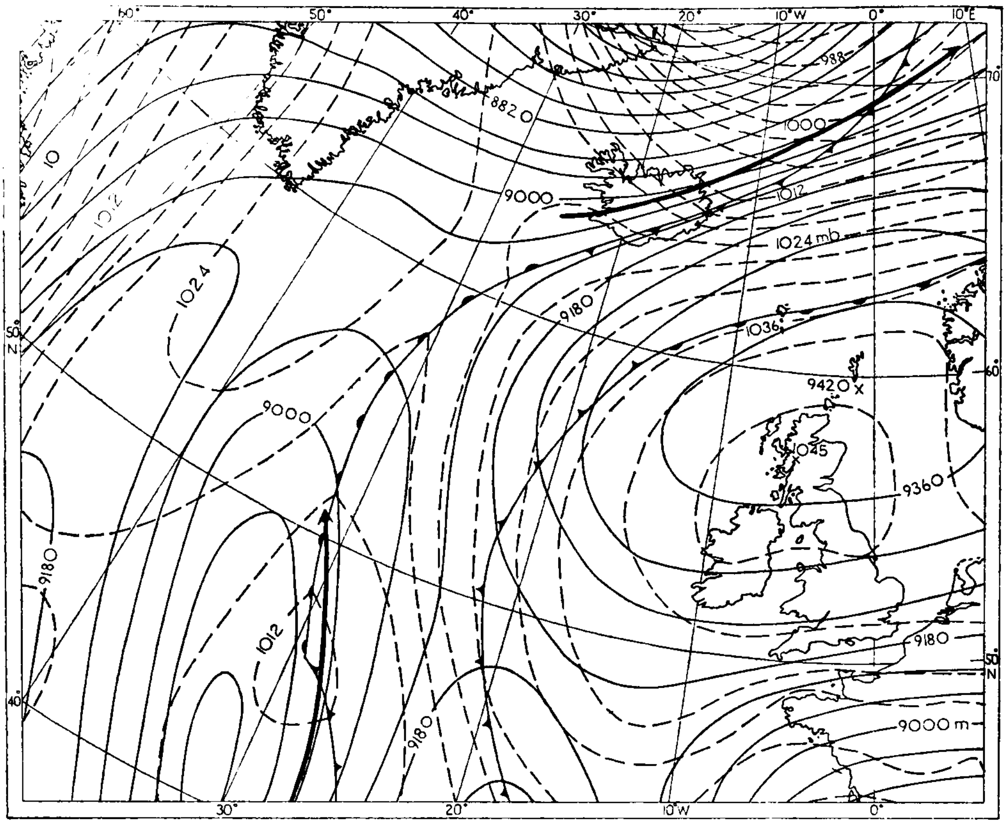
(*a*) 1200 GMT, on 6 February 1960



(*b*) 1200 GMT, on 7 February 1960

FIGURE 6—SEQUENCE SHOWING THE VEERING AND BACKING OF A COLD-FRONT TYPE JET

——— 300 mb contours, - - - - surface isobars. Broad arrows show the position of the jets.



(*c*) 1200 GMT, on 8 February 1960

FIGURE 6—SEQUENCE SHOWING THE VEERING AND BACKING OF A COLD-FRONT TYPE JET—*continued*

little change of direction. At its southern end, in latitude 45–50°N, there was some backing. By 1200 GMT on 8 February (Figure 6(*c*)) low 'LE' formed part of an intense low off the coast of north-east Greenland and the strong south-eastward advection of cold air behind it caused a substantial veering of the jet. It split away from the low latitude part and subsequently crossed Scandinavia as a north-west wind. Whereas backing rather than veering is characteristic of a cold-front jet, this example demonstrates the limitations of any empirical rule.

In conclusion it is appropriate to stress that the facts presented in this paper were mostly based on the stronger jet streams. Since the borderline between a jet stream and a belt of strong winds is arbitrarily chosen, one cannot expect a jet to show characteristics which can be narrowly defined. Jet streams, like fronts call for individual assessment in which experience and subjectivity play an essential part.

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THE COMPUTATION OF GEOSTROPHIC WINDS BY OBJECTIVE ANALYSIS

By M. H. FREEMAN, O.B.E., M.Sc.

Introduction.—Measurements of geostrophic winds are often required in meteorological investigations. If a statistical treatment is to be used a large number of observations will probably be needed and the labour of making numerous geostrophic wind measurements from synoptic charts can be considerable. It was therefore decided to use the computer METEOR to analyse sets of pressure values objectively and evaluate the resulting geostrophic winds. For the period since January 1957 most of the data required have been punched on cards, and it is possible for the pressure values to be converted to punched tape by machine methods. The production of tapes for a network of stations covering the whole British Isles would entail a fairly considerable amount of work, but once the tapes were available, geostrophic (and gradient) winds for any location within the network could be run off on METEOR at a rate of about 30 per minute.

Description of the METEOR programme.—The computer has been programmed to 'read in' a series of surface pressure values from data tapes for up to 22 stations, and checks are included to ensure that each group of data has the correct number of observations. The grid co-ordinates for each station precede the relevant pressure data. The co-ordinates of the position for which winds are required (normally near the centre of the network of reporting stations) are then fed into the machine.

If x and y are the distances east and north of a given station from the selected central position (which becomes the origin), and p is the pressure then the machine derives a formula

$$p = ax^2 + bxy + cy^2 + dx + ey + f \qquad \ldots (1)$$

where the coefficients a,b,c,d,e and f are chosen so as to produce a quadratic surface which is the best fit to the set of observed pressures. The usual criterion that the value of the sum of the squares of the errors shall be a minimum is used. If a particular value, say 1000 mb, is given to p then equation (1) is the equation of the 1000 mb isobar; if p is made equal to f then we have the equation of the isobar through the origin. The pressure gradient may be found by differentiating equation (1), and hence the geostrophic wind can be calculated. The wind speed depends on the latitude, pressure and temperature. The first two are known from the data on the tapes, but an assumed average value, 10°C, had to be used for the temperature. The results will be in error by $3\frac{1}{2}$ per cent for each 10°C by which the temperature differs from 10°C.

In order to provide some information on the accuracy with which the observations have been fitted, the root mean square error between the fitted and the observed pressures is calculated, and the largest individual error is examined. If a large error occurs it is quite likely that it is due to a mistake in the data, and whenever the error is greater than one millibar a statistical test is carried out to examine the likelihood of the observation being wrong. If the fit as a whole is not very good, as sometimes happens for example with strong winds and large tendencies, rejecting an apparent error as large as one millibar may not be justified. The largest error is compared with the standard error of the remaining pressure values using Student's t-test. (If n is the total number of pressure values, then both the standard error and the value of t are based on $n - 7$ degrees of freedom.) If the largest error fails this test, and the corresponding pressure value can then be considered to be wrong with at least a 95 per cent probability, the offending pressure is rejected and the formula is recomputed using one less station. The process of checking and rejecting is continued until all pressures are acceptable or only six are left, when the data will be fitted exactly. The errors in any rejected pressures are recomputed using the finally accepted formula. Lastly the winds and errors are printed and tapes of wind speed and direction are punched.

Comparison between computed and measured winds.—A set of 1012 geostrophic winds for London (Heathrow) Airport at 0600 GMT in November, December and January 1946–57 were available from another investigation. They had been measured by hand from hourly synoptic charts prepared in the Central Forecasting Office and were used for comparison with computed winds for the same period. METEOR was used to work out the vector difference between each pair of winds. There did not appear to be any systematic differences between the two sets of winds, but out of 1012 occasions there were 69 with vector differences of 15 knots or more. An independent remeasurement of the geostrophic wind was made for each day with a large discrepancy, the isobars being carefully redrawn when necessary. This check revealed a number of serious mistakes in the original measurements, even though a good deal of trouble had been taken to get a good set of data. After remeasurement 50 of the 69 discrepancies were reduced to less than 15 knots. Of the 19 large discrepancies which remained 9 occurred when there was a front with a sharp trough near London and the machine had fitted a smooth curve instead of the discontinuity normally drawn. The other 10 discrepancies were caused by the machine not rejecting observations which a skilled analyst, having a much wider network, would have discarded. Nevertheless, on the whole, agreement between computed and measured winds was very good; on 85 per cent of occasions the vector differences were less than 10 knots, 13 per cent of the time they were between 10 and 14 knots, and there were only 2 per cent of discrepancies of 15 to 25 knots. On balance the computed winds were slightly better than the measured winds since before correction the latter had 7 per cent of errors greater than 14 knots.

Choice of network.—Several experiments were made to determine the best network of pressure reporting stations. A network covering too small an area would produce a very local and possibly unrepresentative wind, whereas too large a network might introduce too much smoothing. A quadratic surface cannot fit an inflexion; over a small area this will not matter, but poor results could sometimes be expected over a large area.

The figures quoted in the previous section related to a network of 15 to 18 stations extending 80 to 100 miles to the north and west of London, but only 50 to 70 miles to the south and east. It was evident that sparsity of data to the south-east had contributed to some of the poorer results, but on the whole this network could be considered satisfactory for the computation of geostrophic winds. Trials were made with fewer stations, and results were very nearly as good when the network was reduced to one central station and 9 around the edges. However with as few as 10 stations one wrong report may be rather serious.

At this stage in the investigation an addition was made to the METEOR programme so that the radius of curvature of the isobar through the origin and the gradient wind were also printed out. Only a short series of hand measurements of gradient wind were available for comparison, but it appeared that the computed curvature was frequently too great. This is probably because the fit of the objective analysis will tend to be least good around the edges and if the edges of the network are too close to the central station then noticeable errors may occur in the curvature of the isobars. Trials were therefore made with a wider network consisting of one central station, 6 equally spaced at a radius of about 75 miles and 12 at a radius of about 150 miles. Several continental stations were used in this wider network. The computed geostrophic winds were almost as good as those derived from the smaller network, but the gradient winds showed a marked improvement. There was rarely more than a few knots difference between the cyclostrophic corrections computed on METEOR and those derived from the hand measurements. To investigate the differences, an independent set of hand measurements was made; the differences between the two sets of measurements were comparable in size with the differences between the computed and the measured cyclostrophic corrections. This emphasizes the subjective nature of measurements of curvature and the difficulty of obtaining reliable gradient winds. Boyden[1] concludes that except with marked cyclonic curvature it is better to use the geostrophic rather than the gradient wind, and a comparison with the Crawley 900-metre wind for the short run of data examined supported this opinion.

Occasions will arise when geostrophic winds will be required for a coastal station where it is impossible to provide a network surrounding the station. In order to assess the accuracy attainable in these circumstances, winds were computed for London based on a network of 22 stations to north of a line Portland Bill–London–Felixstowe. The accuracy of the geostrophic winds so obtained was about as good as that of the networks with London in a central position, but the gradient winds were not very good.

Probably the optimum network would consist of about 10 stations at a radius of 80 to 100 miles from the central point together with 5 or 6 stations equally spaced within the circle. If gradient winds are important and a slightly lower general standard can be accepted, then some of the closer stations should be replaced by 5 or 6 others at a radius of 120 to 150 miles.

Errors in pressure data.—A by-product of the computations is the information on suspected errors in the pressure data. On examination a fairly large proportion of the errors proved to have been made during the extraction and taping of the reports. These were corrected and there remained, out of nearly 9000 pressure values, 41 which were suspected of having errors; for these occasions the records were carefully examined, and 25 mistakes were found. On the other 16 occasions, when the suspected errors ranged from 1.3 to 3.2 mb, there was no other evidence to indicate that the records were incorrect. Thus, on this sample of data, the programme served the useful purpose of identifying pressures which had been wrongly entered in the records on about 0.2 per cent of occasions.

Conclusions.—The objective analysis of a set of pressure values by computer provides a satisfactory technique for the calculation of a series of geostrophic winds. The values obtained will be slightly more reliable than those resulting from hand measurements from synoptic charts unless particular care is taken in the analysis. The extraction and taping of the necessary pressure data is not however a trivial job.

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551.579.2

WATER YIELD FROM SNOW

By A. B. THOMSON, M.A.

Introduction.—Various authors in *British Rainfall,*[1] *Symons's Meteorological Magazine*[2] and the *Quarterly Journal of the Royal Meteorological Society*[3] give the amounts of water obtained by melting samples of freshly fallen snow. Colonel Ward of Calne, Wiltshire, and J. H. Dyson of The Old Vicarage, Preston, Canterbury, provided most of the data. Some of Colonel Ward's investigations were made in Switzerland, but his results and those of others show that, in general, the mean depth of snow required to produce an inch of water varies from about 9 inches to around 12 inches. The least is about 5 inches and the most about 35 inches in Britain, though two extreme cases from Switzerland are quoted by Colonel Ward, where 50 inches and 113 inches of snow produced only one inch of water.

This paper presents the relationship between snow depth and water yield which has been found from snow samples taken in Scotland.

Data used.—In December 1955, the City Engineer, Aberdeen, arranged for a number of his rain-gauge stations in the catchment area of the River Dee to measure each morning the depth of snow which had fallen in the preceding 24 hours on a flat board laid on the ground, or on top of previously fallen snow in the vicinity of the rain-gauge. Using the inverted funnel of the rain-gauge, a cylindrical snow sample was then cut from the full depth of measured snow on the board. The sample was melted and measured in the glass rain measure to obtain the water yield. The board was swept clean after each observation.

Equivalent snow depth.—A total of 381 observations of snow depth were made at the seven stations listed in Table I during the period December 1955 to December 1961. Each of these observations was used to calculate the 'equivalent snow depth', i.e. the depth of snow that would be required to yield one inch of water.

TABLE I—MEAN 'EQUIVALENT SNOW DEPTHS' CALCULATED FOR STATIONS IN THE DEE CATCHMENT AREA

Station	Elevation	National grid reference	Number of samples*	Mean 'equivalent snow depth'
	feet			*inches*
Derry Lodge	1400	37/036932	127	11.9
Inchnabobart	1270	37/310876	116	10.7
Gairnshiel Lodge	1100	38/295008	24	12.7
Braemar Irrigation Farm	1060	37/148921	25	9.4
Ballater Irrigation Farm	633	37/381966	44	10.8
Tarland Irrigation Farm	467	38/488040	17	11.9
Aboyne Irrigation Farm	380	37/542982	28	11.9

*All available samples between December 1955 and December 1961.

The resulting combined data are shown in the form of histograms in Figure 1, each histogram indicating, in addition to the 'equivalent snow depth,' the various actual depths of the snowboard samples comprising the group. For example, the modal group contains 92 cases in which the 'equivalent snow depth' ranged from 12.0–12.9 inches, the 92 cases being made up of 51 snowboard samples of depth less than 3 inches, 25 of 3–5.9 inches, 10 of 6–8.9 inches and 6 of 9 inches or more.

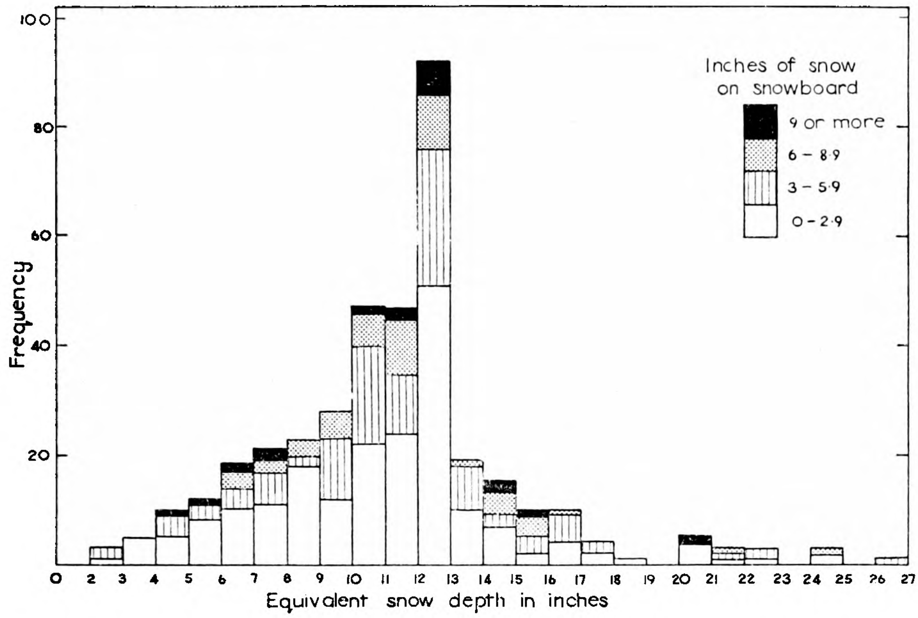


FIGURE 1—FREQUENCY OF 'EQUIVALENT SNOW DEPTHS' YIELDING ONE INCH OF WATER

Although Figure 1 shows the depths in one-inch classes for convenience, the observations were initially tabulated in ½-inch classes and the mean and standard deviation calculated from the latter distribution. The mean 'equivalent depth' found was 11.23 inches with a standard deviation of 3.75 inches while 94.8 per cent of the observations were no further from the mean than twice the standard deviation (i.e. equivalent depths 3.7–18.7 inches). The mode lies in the range 12.50–12.99 inches.

To determine whether there was any significant difference in the mean 'equivalent depths' found for light snowfall and for heavy snowfall, the means were also calculated separately for snowboard depths of less than 3 inches and for depths of 3 inches or more. In both cases the mean value was approximately 11 inches. The mean 'equivalent depths' were also determined for each station separately. These are shown in Table I together with the number of samples examined for each station.

Over the five winters from 1937 to 1942 J. H. Dyson[3] recorded the water equivalent of melted snowfall at The Old Vicarage, Preston, Canterbury. The annual means of 'equivalent depths' providing one inch of water were 10.8 4.7, 11.1, 9.0 and 10.9 inches, giving a mean over the five years of 9.3 inches.

Table II lists the frequencies, at the Deeside stations, of the various actual depths of the snow on the snowboards during the same period as for Table I. It will be seen that slightly more than half the samples were under 3 inches deep. There is no reason to doubt that the samples are reasonably representative of upland areas.

TABLE II—FREQUENCY OF VARIOUS ACTUAL DEPTHS OF SNOW OBSERVED AT STATIONS IN THE DEE CATCHMENT AREA

Depth of snow on snowboard (*inches*)	< 1	1–1.9	2–2.9	3–3.9	4–4.9	5–5.9	6–6.9	7–7.9	8–8.9	9–9.9	>9.9
Number of samples	64	71	66	48	37	25	25	16	11	3	15

Temperature effect.—The 381 'equivalent snow depths' for the seven stations (Table I) were tabulated against the mean daily temperature ($\frac{1}{2}$ maximum + $\frac{1}{2}$ minimum) at Braemar for the 24 hours preceding the time of observation. The temperatures used were those recorded at the Braemar Climatological station, whose elevation is 1111 feet—comparable to the mean height of the 7 stations. Five of the samples were taken when the temperature was under 17°F and five when above 39°F, but for convenience these were included with the samples taken at 17° and 39° respectively. Figure 2 shows the relationship graphically for 3° and 6° intervals, the values being plotted at the mid-points of the intervals.

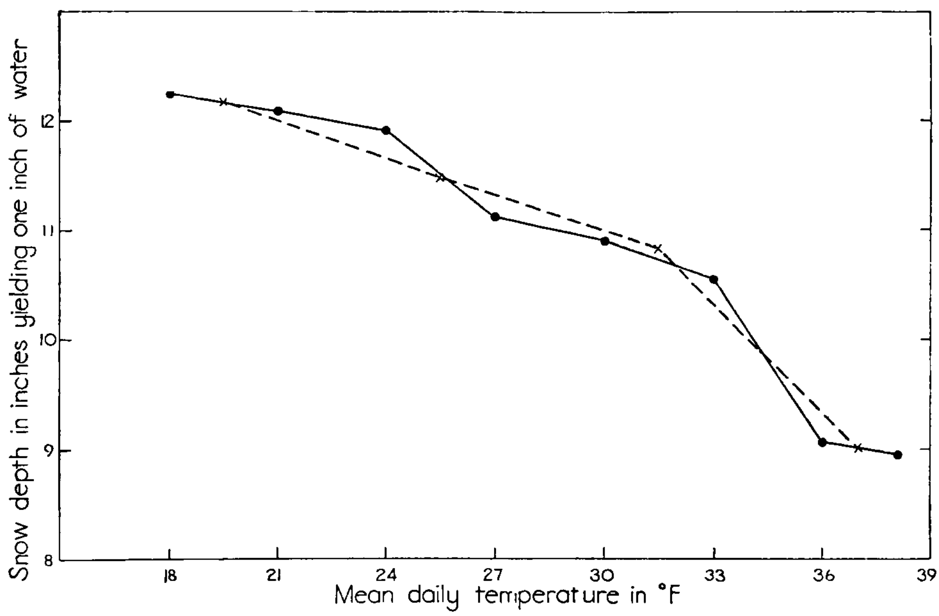


FIGURE 2—RELATION BETWEEN 'EQUIVALENT SNOW DEPTH' AND MEAN TEMPERATURE

•———• 3° intervals, x - - - x 6° intervals.

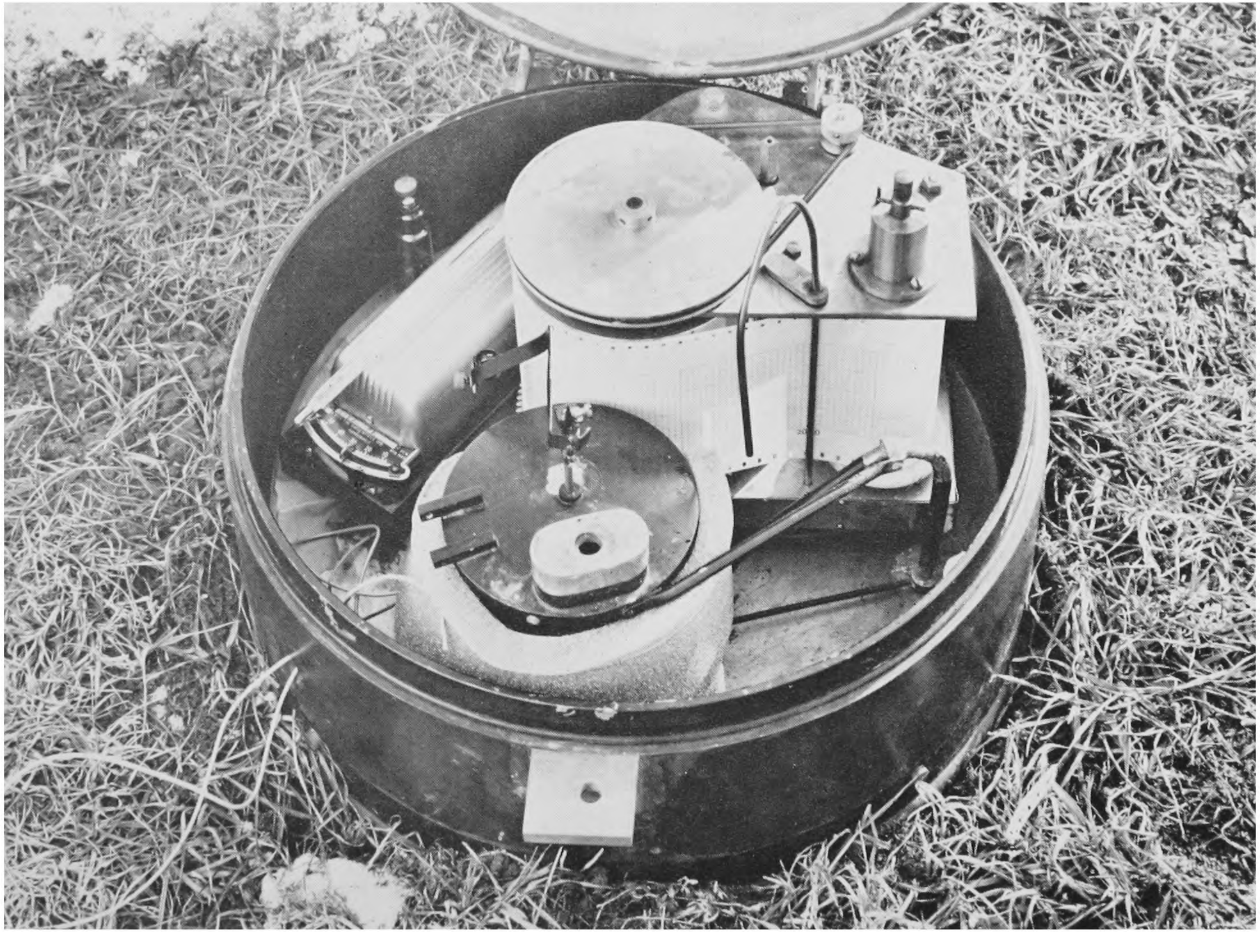
Values are taken at the mid-point of the interval.

As one would expect, there is a steady increase with temperature in the water yield per inch of snow from the samples, and a sharp increase around the freezing-point.

Photograph by R. K. Pilsbury

PLATE I—RIME ON CHAIN-LINK FENCING (2-INCH MESH)

This photograph was taken at Bracknell at 1800 GMT on 24 January 1963 after a day of fog and temperatures below freezing. A black cloth provided the background and flash was used to give sparkle.



By courtesy of the Hydraulics Research Station *Crown copyright*

PLATE II—MODIFIED RAIN-RECORDER WITH EIGHT-DAY STRIP CHART MECHANISM, EQUIPPED WITH LOW-VOLTAGE HEATING AND WALL THERMOSTAT

Note the lagging round the chamber. (See p. 337.)

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PLATE III—STANDARD RAIN-RECORDER WITH LOW-VOLTAGE HEATING SYSTEM AND SMALL THERMOSTAT
(See p. 338.)

To face p. 335

By courtesy of the Hydraulics Research Station

PLATE IV—TWO RAIN-RECORDERS SHOWING ACCUMULATORS FOR LOW-VOLTAGE HEATING SYSTEM

(See p. 338.)

Conclusions.—The large standard deviation of the 'equivalent snow depths' (nearly 4 inches) shows the imperative need to obtain the actual water equivalent by melting wherever possible. The use of a conversion factor 1/10 (or 1/12 as recommended in *Rules for rainfall observers*[4]) can be regarded as a poor substitute method to be used only as a last resort when melting cannot be carried out.

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551.508.77:551.524.37

A NOTE ON THE OPERATION OF RAIN-RECORDERS DURING COLD WEATHER

By J. C. RODDA, B.Sc., Ph.D.

(Hydrological Research Unit, Hydraulics Research Station, Wallingford, Berks.)

Introduction.—The continuous operation of any Meteorological Office standard rain-recorder in weather conditions like those experienced during the 1962–63 winter is an extremely difficult task. The float in the collecting chamber has to be protected against frost damage, and the capability of the gauge to record rain and other forms of precipitation has to be maintained during frosty weather. This paper briefly considers the problem, and describes field trials of an electrical method of heating a rain-recorder by means of an accumulator. The system which results is an approach to a recorder which would function at an isolated site for a week under frosty weather conditions without attention or refuelling, but it is not designed for snow measurement.

Frost protection.—

(i) *Anti-freeze.*—Apart from removing the float chamber unit, perhaps the simplest way of affording frost protection is to make periodic additions of a freezing-point depressor to the rain-water standing in the collecting chamber. The volume of liquid that needs to be added for a particular level of protection can be calculated, but dilution by rain falling between additions can make this method ineffective.

(ii) *Use of plastic material.*—Ice formed in the collecting chamber because of frost can distort or puncture metal floats, but some successful experiments[1] in the use of plastic floats have been carried out recently as part of the Meteorological Office rainfall investigation near Winchcombe, Gloucestershire. When these floats were examined after being employed in standard rain-recorders exposed to temperatures as low as −20°C, it was found that the plastic floats had suffered no damage.

(iii) *Heating.*—Frost damage can be prevented by arranging for the gauge to be heated by a small heat source. The heating required is discussed more fully in later paragraphs.

Recording during frosty weather.—While these measures prevent damage to the float, they are not effective ways of ensuring that the recorder will function in freezing conditions when further precipitation occurs, whether it falls as rain, snow or in some other state. So that the gauge will operate in these circumstances heat has to be injected into it, the amount depending upon the form of the precipitation. The largest amount of heat is required by the recorder when it is operating as a gauge to record the amount and rate of snowfall. Then enough heat has to be supplied to maintain the gauge's interior temperature above freezing-point and melt the snow as rapidly as it falls into the funnel. However, since the gauge is not designed for collecting snow, it is doubtful whether the complications involved in producing and controlling the necessary heat would be justified by the record which would be obtained. As a result it was decided to design a heating system using a lesser amount of heat which would protect the float mechanism and allow the gauge to record 'rainfall' in temperatures below freezing-point.

As there are obvious limitations to the use of mains electricity the installation of a 25-watt lamp inside the recorder, as advised by the Meteorological Office,[2] was not carried out. The alternative, two night-lights placed below the funnel, was also rejected, one reason being that unless ventilation is carefully adjusted excessive condensation can occur which will ruin any chart record. A reliable, self-contained heating system was sought, not employing a flame burning inside the recorder, but utilizing instead heat produced by a source outside the gauge.

Evaluating the heating requirement.—To determine what quantity of heat was required to prevent freezing in the collecting chamber, a cooling experiment was performed on a rain-recorder in the laboratory. The time taken for water in the collecting chamber, at a known temperature, to cool to room temperature was measured by stop-watch and thermistor thermometer, the thermistor being placed in the collecting chamber. The experiment was repeated for various volumes of water between 100 cm^3 and 200 cm^3 and over a range of temperatures from 5.4°C to 14.0°C above room temperature. From these measurements, and after determining the water equivalent of the collecting chamber, it was possible to deduce that the average rate of heat loss was approximately 0.4 cal/sec for these volumes of water and range of temperature. Assuming that the experiment simulated the effect of nocturnal cooling in the field, it followed that heat must be put into the chamber at a rate greater than 0.4 cal/sec to maintain the chamber temperature just above 0°C with an outside temperature of about –5°C. It was considered that with lagging and a heat source producing between 0.8 and 1.0 cal/sec, the collecting chamber might remain unfrozen and able to accept rain-water in temperatures as low as –10°C. Several attempts to confirm these figures have been made by carrying out cooling experiments in the field, but these have been difficult to conduct because of changes in air temperature and wind velocity during the experiment. However measurements have been made giving values between 0.5 cal/sec and 0.9 cal/sec for the average rate of cooling for 100 cm^3 and 200 cm^3 of water up to 10°C in excess of the ambient temperature.

Heating system.—

(i) *Hot air.*—Experimental work was commenced to find a suitable heating system first using several types of small paraffin heaters, the hot air generated being conducted through the rain-recorder within a narrow-bore copper tube. The tubing was coiled inside the walls of the lower part of the gauge and finally led out through the window in the side of the funnel housing. Although several modifications were made to the heater housing, which acted as a duct for the hot air from the heater, the temperature inside the gauge could not be raised more than 1°C above room temperature. It is probable that with a larger flame and a more efficient heat exchanger the temperature increase inside the gauge would have been greater.

(ii) *Water circulating system.*—The Department of Forestry at Oxford University has had considerable success in heating a rain-recorder using first butane gas then paraffin as fuels.[3] A water circulating system was employed with a flame heating a boiler sunk in a pit alongside the gauge, the whole gauge being heated from a coil of copper tubing under the funnel.

(iii) *Electrical.*—An electrical method of heating was eventually chosen for this project because of the difficulties of using a flame-heated circulating system, particularly at water-logged sites. The comparatively small amount of heat required to maintain the collecting chamber at a temperature above freezing can be produced efficiently by an accumulator. An experiment was conducted with a 12-volt accumulator and a length of heating tape as this seemed to be an efficient way of heating the chamber. There are several types of this plastic-covered heating tape available; some can be used over a range of voltages and in various lengths for different outputs; others are meant to be run at the mains voltage so producing a fixed amount of heat. A length of this second type of tape was employed but at 12 volts d.c. rather than that intended by the makers. At this voltage it was found that the resistance was 2.6 ohms/in., so that an output of approximately 1 cal/sec was achieved with 13 in. of tape and 0.8 cal/sec by a length of 16½ in.

Trials of equipment in cold weather.—Field tests of the heating system were commenced at the Hydraulics Research Station on 4 January 1963. A standard Meteorological Office rain-recorder had been modified to the specifications of the Road Research Laboratory (L. H. Watkins[4]) by substituting an 8-day strip chart mechanism for the standard clock, sealing all unnecessary holes in the gauge to make it damp-proof, and fixing the tilting chamber so that it emptied by siphoning alone. A 13-in. length of tape was wound around the collecting chamber of the gauge and connected to an accumulator by a circuit which included a wall thermostat set at a little above 0°C. Apart from reasons of economy of current the thermostat was used to prevent overheating of the collected rain-water. Ideally it should have been set in the collecting chamber but no model could be found which was sufficiently small for this.

This system operated for a week at temperatures shown in Table I before the quarter-full collecting chamber became frozen on 10 January 1963. As an additional measure, the sides of the chamber were lagged including the heating strip (see Plate II) and the gauge operated successfully in this state until 23 January when it froze for a second time. The addition of a small quantity of anti-freeze prevented the same thing happening on the following night when the air temperature fell to almost −16°C.

TABLE I—MINIMUM TEMPERATURES RECORDED AT THE HYDRAULICS RESEARCH STATION, WALLINGFORD, DURING JANUARY 1963

Date (January)	4	5	6	7	8	9	10	11	12	13	14
Air temperature in °C	−1.1	−1.4	−1.4	−2.1	−2.2	−7.9	−9.3	−11.8	−13.6	−6.7	−8.2
Grass temperature in °C	−0.7	−3.1	−1.4	−3.1	−3.4	−10.0	−10.9	−14.3	−14.5	−6.7	−10.4

Date (January)	15	16	17	18	19	20	21	22	23	24
Air temperature in °C	−7.3	−6.7	−9.5	−9.8	−6.8	−6.4	−4.2	−13.7	−16.0	−15.8
Grass temperature in °C	−9.4	−6.5	−11.0	−12.6	−8.9	−7.5	−6.8	−12.9	−15.9	−15.9

At a later date a standard rain-recorder was lagged and equipped with the same type of heating system (see Plate III). In this case a heating strip producing 0.8 cal/sec was used, and after lagging the top and sides of the collecting chamber, a test was made to ensure that tilting occurred at the same point as before modification. Because of the limited amount of space available in this gauge a thermostat of the type used in convector heaters was included in the circuit, rather than the more bulky but more sensitive variety used before. Although temperatures in February did not fall to January levels this gauge continued to function at temperatures well below freezing-point (e.g. on 25 February; −10.8°C air minimum, −13.2°C grass minimum).

Both rain-recorders were heated by current produced from standard 50 ampere-hour accumulators housed alongside the gauges in wooden boxes (see Plate IV). The life of these accumulators was more likely to be between 35 and 45 ampere-hours when fully charged, and so to avoid running them to exhaustion a change was made every 3 to 4 days during the coldest weather and then at intervals of 5 to 6 days when conditions were less severe. In the worst possible weather with current being consumed continuously, one 70 ampere-hour accumulator would provide ample power to protect a rain-recorder for one week, but if temperatures were not below freezing-point all the time one 50 ampere-hour accumulator might be sufficient. No doubt greater thermal efficiency could be achieved by lagging the outside of the gauge and around its base, but without making a complete change of design the other points in the recorder susceptible to freezing could not be heated by this method unless a wind generator or similar charging device could be incorporated in the system.

Acknowledgements.—This paper is published by permission of the Director of Hydraulics Research. The assistance of Mr. A. L. Maidens and several other staff of the Meteorological Office has been of considerable importance in the preparation of this paper, and their help together with that given by the author's colleagues is gratefully acknowledged.

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551.586:612

AN INDEX OF COMFORT FOR SINGAPORE

By P. M. STEPHENSON, M.Sc.

Introduction.—A superficial examination of the climatological data for Singapore, which is situated about 80 miles north of the equator, indicates an annual monthly-mean temperature range of only 3°F and humidity range of only 4 per cent (see Table I). This might lead one to believe that the climate was uniformly hot, humid and unpleasant throughout the year. This runs completely contrary to all experience which, even with Europeans who have been resident in Singapore for years, indicates that one feels distinctly more comfortable at some times of the year than at others irrespective of the time of day.

Consideration of this point leads to a search for an easily recognizable index of comfort and the simplest index which has been suggested is wet-bulb temperature. As a point of interest it has been suggested that the upper limit of wet-bulb temperature for *sustained* white labour is about 78°F. The annual range of average 24-hour wet-bulb temperature in Singapore is only 3°F with a minimum of 75°F in January and a maximum of 78°F in May so that clearly the wet-bulb temperature is not a particularly useful criterion in Singapore.

Other indices which have been suggested by different authorities are based on one or more of the elements: temperature, humidity and wind speed. A convenient and apparently very satisfactory scale taking into account temperature, humidity and wind speed, is the 'effective temperature' scale devised by the American Society of Heating and Ventilating Engineers (ASHVE).[1]

Effective temperature.—'Effective temperature' is defined as "that temperature of saturated motionless air which would produce the same sensation of warmth or coolness as that produced by the combination of temperature, humidity and air motion under observation," and it will be evident that the effective temperature is dependent upon the amount of clothing worn. ASHVE obtained two scales by calibrating the opinions of a group of trained observers, either stripped to the waist or lightly clad, who passed back and forth between two adjoining air-conditioned rooms in which the temperature was varied but the air was maintained fully saturated and with a constant air movement.

Nomograms relating effective temperature to dry-bulb and wet-bulb temperatures and wind speed for the two categories of clothing are published by the Air Ministry.[2] For the purposes of this note the scale appropriate to lightly clad persons only has been used.

The 'comfort zone' of effective temperature (i.e. the zone within which the majority of individuals will be content and able to work at maximum efficiency), for acclimatized persons in hot regions is 66° to 76°F with an optimum of 69°F. If maximum efficiency is to be obtained from sedentary workers, 76° to 78°F is considered the highest permissible effective temperature. The critical effective temperature, above which muscular effort would cause the body temperature to rise rapidly to danger level, is probably between 85° and 90°F. It is possible to do sedentary work at 90°F effective temperature, but owing to discomfort it may not be particularly productive.

Since the effective temperature in Singapore rarely, if ever, exceeds 85°F, outdoor sports can be safely indulged in at all times of the year provided the participant can, or does not mind that he does, perspire freely.

Summary of data used.—Climatological data for Singapore Airport (located at Kallang until July 1955 and at Paya Lebar subsequently) are published regularly, and 10-year means (1952 to 1961) of dry-bulb temperature and relative humidity were calculated for each month of the year (Table I) together with mean scalar wind speeds (Figure 1).

TABLE I—MEAN DRY-BULB TEMPERATURE AND RELATIVE HUMIDITY FOR SINGAPORE AIRPORT (1952–61)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						degrees Fahrenheit						
Mean dry-bulb temperature	78	79	80	81	81	81	81	81	80	80	79	78
						per cent						
Mean relative humidity	85	83	84	85	85	83	84	84	84	84	86	87

Mean wet-bulb temperatures which were not readily available were deduced from the mean values of dry-bulb temperature and relative humidity using hygrometric tables. The values thus obtained would be slightly higher than true means calculated from hourly readings of the wet-bulb thermometer, but the error would rarely exceed 1°F.

The corresponding mean 24-hour effective temperature, as read from the appropriate nomogram, together with the dry- and wet-bulb values are plotted in Figure 2.

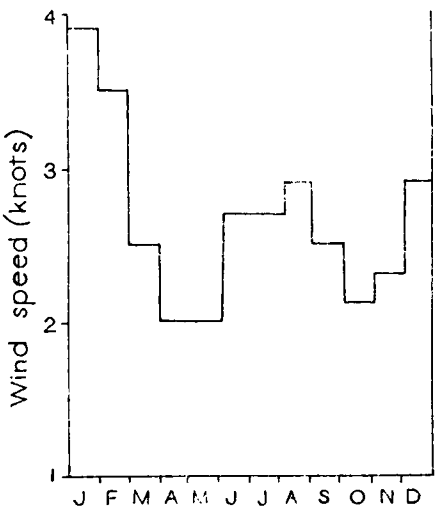


FIGURE 1—MEAN 24-HOUR SCALAR WIND AT SINGAPORE AIRPORT (1952–61)

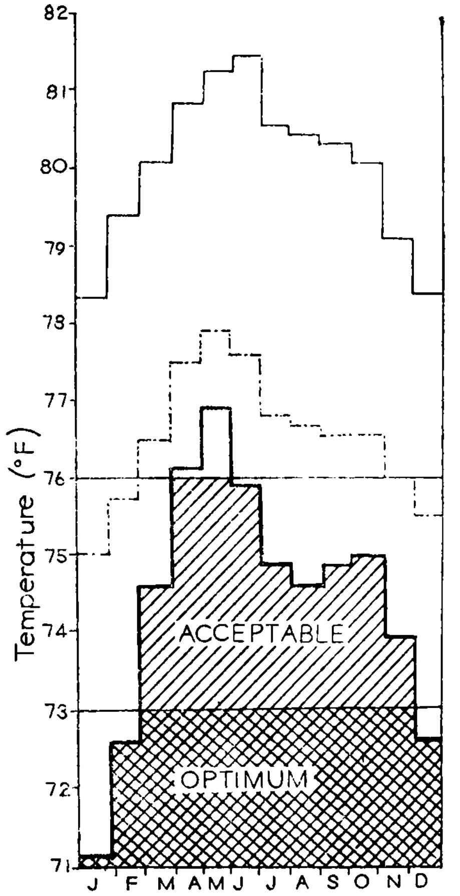


FIGURE 2—MEAN 24-HOUR TEMPERATURES AT SINGAPORE AIRPORT (1952–61)

—— dry-bulb temperature, –·– wet-bulb temperature
▬▬▬ effective temperature

Three-hourly values of dry-bulb and wet-bulb temperatures and wind speed for a 5-year period (1951 to 1955) which were readily available for Changi Airport were used instead of data from Singapore Airport to assess the diurnal variation of effective temperature. These observations also enabled a comparison to be made between Changi, which is located on the eastern end of Singapore Island, and the Paya Lebar–Kallang area which is on the eastern outskirts of Singapore City nearer the centre of the Island.

The variations of dry-bulb and wet-bulb temperatures, wind speed and effective temperature over 24 hours for each of the months January, April, July and October for Changi are shown in Figures 5 and 6, whilst in Table II a comparison is made between Singapore Airport and Changi Airport.

Figures 3 and 4 show the effective temperatures which would correspond to various wind speeds at 0430 and 1330 zone time in an average April at Changi, assuming that dry-bulb and wet-bulb temperatures at each of these hours were fixed at the appropriate average values.

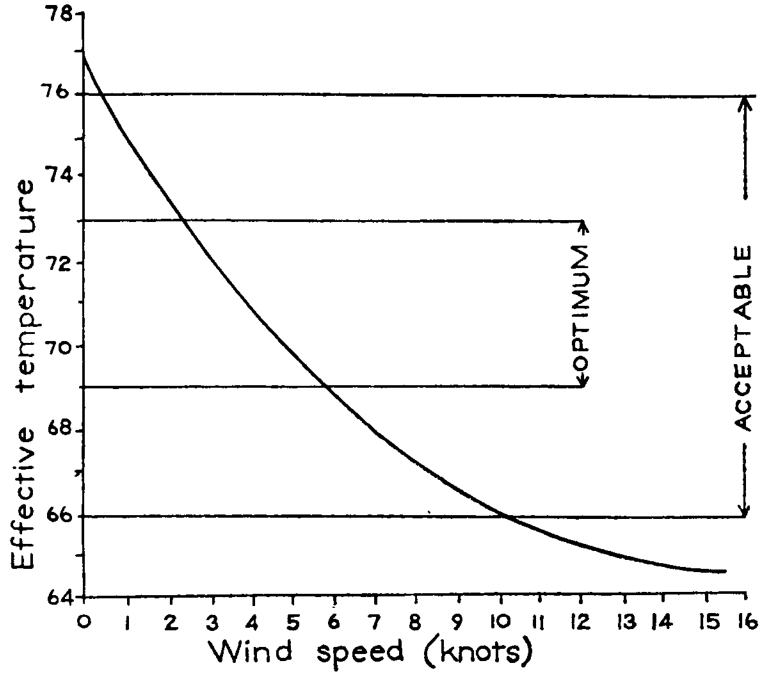


FIGURE 3—VARIATION OF EFFECTIVE TEMPERATURE WITH WIND SPEED AT CHANGI AT 0430 ZONE TIME FOR AN AVERAGE APRIL
(average dry-bulb temperature 77.7°F)
(average wet-bulb temperature 76.0°F)

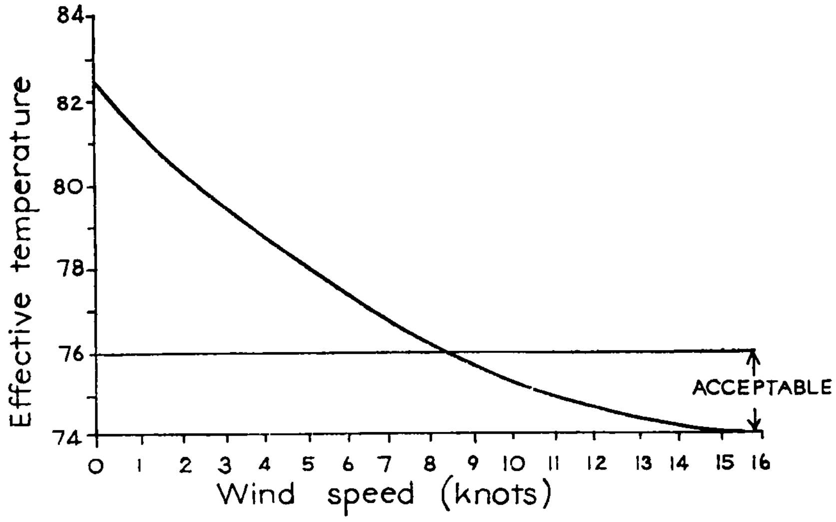


FIGURE 4—VARIATION OF EFFECTIVE TEMPERATURE WITH WIND SPEED AT CHANGI AT 1330 ZONE TIME FOR AN AVERAGE APRIL
(average dry-bulb temperature 87.6°F)
(average wet-bulb temperature 79.0°F)

Discussion of data.—

1. *Annual variation of effective temperature.*—Figure 2 shows that January is by far the most comfortable month in Singapore and that two periods, namely April to June and September to October, are the least comfortable. This accords with experience and also to a slight degree, with the dry-bulb and wet-bulb temperatures except in October. However these latter temperatures do not indicate the *extent* to which January differs from May, which is due largely to the combination of high wind speed and low temperature in the former contrasted with low wind speed and high temperature in the latter. The two minima of effective temperature in January and August occur one to two months after the solstices, when the sun is at its furthest from Singapore, and when the north-east and south-west monsoons respectively are producing a steady flow of wind over the Island. The two maxima in May and October occur similarly after the equinoxes when the sun is virtually overhead and when the winds are light and variable during the transition stages between the two monsoons.

It can readily be seen from Figure 2 that only in the months December, January and February do the effective temperatures fall within the *optimum range* for hot climates, whilst in April and May the effective temperatures are outside the *acceptable range* for efficient sedentary work. In theory, the effective temperatures indoors could be artifically reduced by means of fans, but Figure 4 demonstrates that on an April afternoon a wind speed of at least 8 knots would be required to bring the effective temperature below the acceptable level, whilst even 15 knots would not produce optimum comfort. The latter would moreover scatter any loose papers far and wide over the office and would not be practicable.

It can be seen from Table I that relative humidity which is considered by many to be a significant factor in comfort is most unreliable, and in fact the most comfortable months have the highest relative humidity.

Table II clearly illustrates the advantage of using effective temperature to assess climate. Inspection of either the dry-bulb or wet-bulb temperatures or both would give the impression that Singapore and Changi Airports had virtually identical climates, whereas the effective temperature, which makes allowance for wind speed, shows that Changi, in fact, enjoys a more comfortable climate than central Singapore. This is consistent with Changi being situated on the more exposed extreme eastern tip of Singapore Island.

TABLE II—COMPARISON OF TEMPERATURES AND WIND SPEEDS FOR SINGAPORE AND CHANGI AIRPORTS

	Mean 24-hour dry-bulb temperature				Mean 24-hour wet-bulb temperature			
	Jan.	Apr.	July	Oct.	Jan.	Apr.	July	Oct.
	degrees Fahrenheit							
Singapore Airport	78.3	80.9	80.6	80.1	75.0	77.5	76.8	76.6
Changi Airport	78.3	81.7	80.7	80.7	75.0	77.3	76.4	76.3

	Mean 24-hour wind speed				Mean 24-hour effective temperature			
	Jan.	Apr.	July	Oct.	Jan.	Apr.	July	Oct.
	knots				*degrees Fahrenheit*			
Singapore Airport	3.9	2.0	2.7	2.1	71.1	76.1	74.9	75.0
Changi Airport	6.5	3.7	4.4	4.1	68.8	74.8	73.1	73.5

2. *Diurnal variation of effective temperature.*—In addition to the annual variation, effective temperature also shows a marked diurnal variation, the nights being generally cooler than the days, as might be expected. What is perhaps somewhat unexpected is that each of the diurnal curves of effective temperature shows a secondary maximum occurring shortly after midnight coinciding with the wind speed minimum.

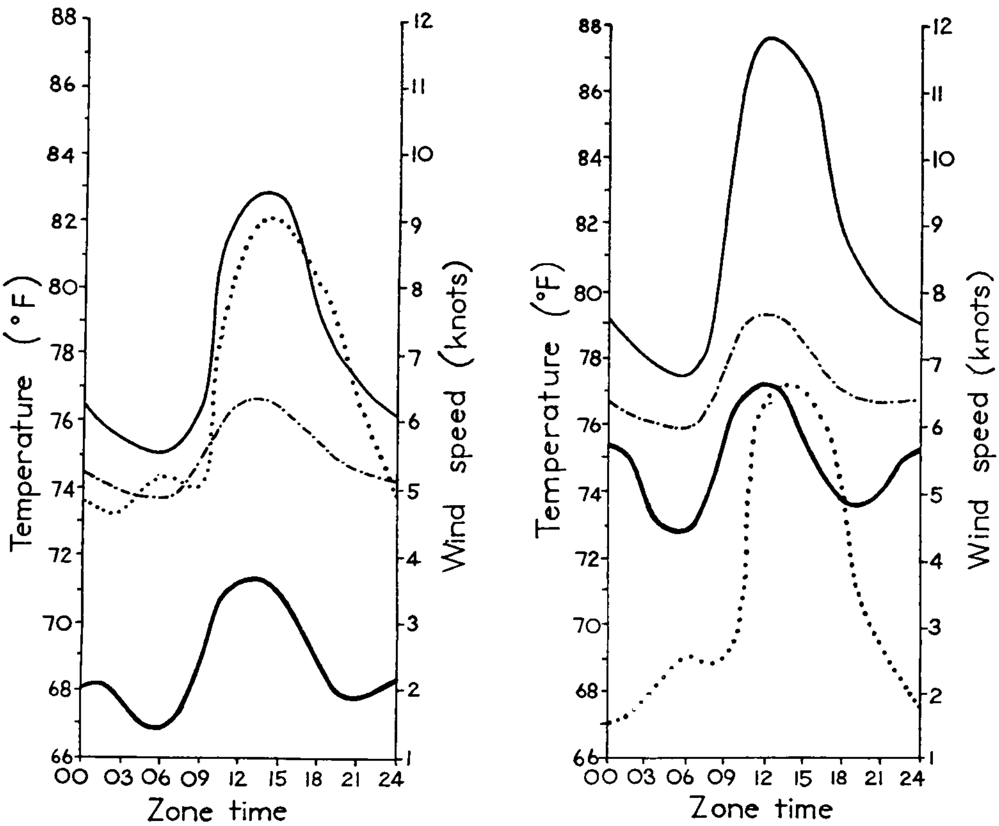
Other points of interest arising from the diagrams of diurnal variation (Figures 5 and 6) are:

(i) The time of maximum discomfort is an hour or so earlier than the time of maximum temperature, the effect of the latter being offset by the corresponding wind speed maximum.

(ii) The most comfortable time of day at all seasons is generally about 0500–0600 zone time with a secondary comfortable period occurring at about 2000.

(iii) Taking 69° to 73°F effective temperature as the optimum comfort zone for the tropics, we can deduce the following:

- (*a*) January is not at any time of the day too hot and in fact during the early hours of the morning the effective temperature is too cool for comfort.
- (*b*) April is uncomfortably hot virtually throughout the 24 hours.



(*a*) January (*b*) April

FIGURE 5—DIURNAL VARIATION OF WIND SPEED AND TEMPERATURES AT CHANGI

———— dry-bulb temperature ▬▬▬ effective temperature

–·–·– wet-bulb temperature .... wind speed

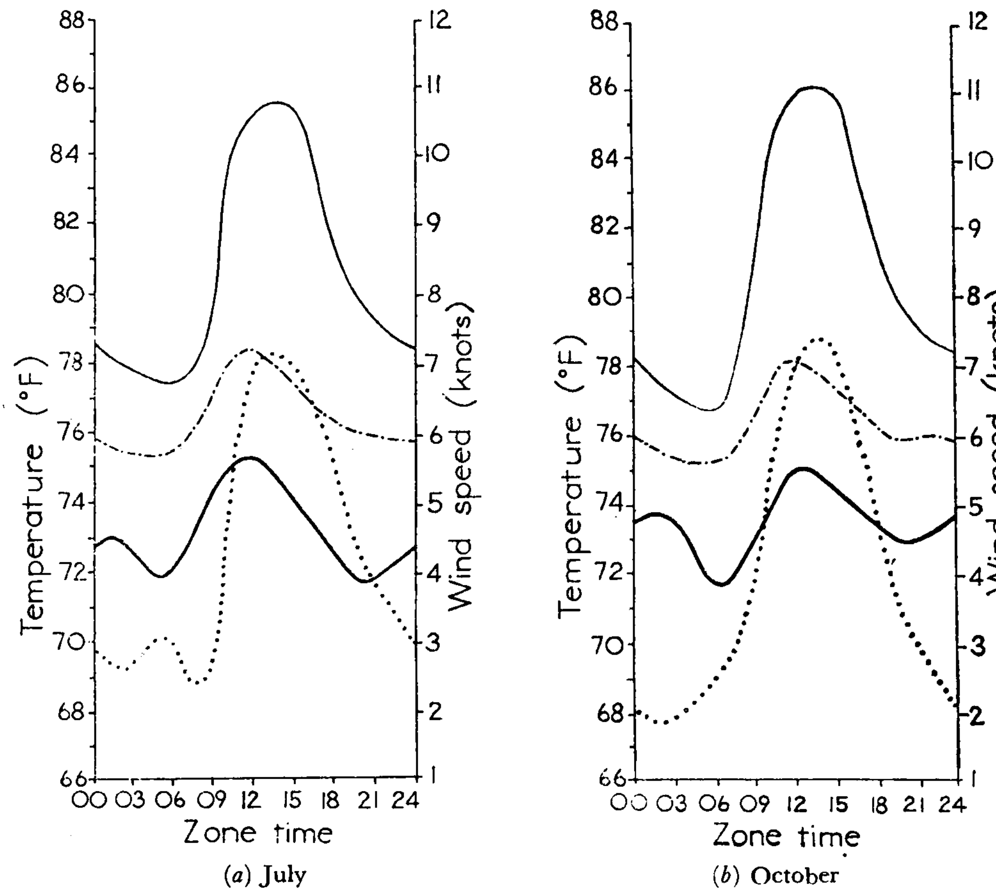


FIGURE 6—DIURNAL VARIATION OF WIND SPEED AND TEMPERATURES AT CHANGI

——— dry-bulb temperature
—·—·— wet-bulb temperature
▬▬▬ effective temperature
.... wind speed

(c) July is uncomfortably hot from about 0800 to 1700 (the normal working day in this part of the world is from 0800 to 1600).

(d) October is uncomfortable for all except 5 (0400 to 0900) of the 24 hours.

(iv) Rather surprisingly at first sight the diurnal variation of the effective temperatures is not as great as that of the corresponding dry-bulb temperatures, whilst the annual variation of the former is greater than that of the latter.

(v) The lowest night time effective temperatures during the warm months are higher than the highest daytime effective temperatures in January.

3. *Effect of rainfall and sunshine.*—The effective temperature index as designed is clearly only applicable to conditions under cover.

Rainfall and sunshine have a bearing on comfort, particularly when working out of doors. In Singapore the temperature during prolonged rainfall is generally in the low seventies so that, with the air almost saturated and in the absence of any wind, the effective temperature would be within the optimum comfort zone. Thus one would expect to feel pleasantly comfortable indoors during rainy spells. This is borne out by experience, it being often unnecessary to switch on any fans at such times. However, a combination of wind and rain, particularly outdoors, can be most unpleasant. Apart from the inconvenience of getting wet, the effective temperature falls below the optimum level, producing uncomfortably cool conditions. Such conditions are most likely to occur during the north-east monsoon when Singapore experiences its highest rainfall (See Table III).

Prolonged exposure to sunshine also produces discomfort, due largely to the actinic rays which are the primary cause of sunburn. The danger from these rays however is greater in dry tropical countries and in the highlands of Malaya than near sea level in Singapore where the water vapour in the air absorbs a large proportion of the ultra-violet. In fact many Europeans in the area do not tan readily. Table III also shows that prolonged bright sunshine is rare in Singapore with an average of less than half an hour's sunshine per daylight hour so that, despite its proximity to the equator, protection against sunshine is not as essential in Singapore as in some other parts of the tropics and subtropics.

TABLE III—MEAN RAINFALL AND SUNSHINE FOR SINGAPORE AIRPORT (1951–61)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
							inches						
Rainfall	9	6	7	6	5	7	6	8	5	7	10	12	88
							hours						
Sunshine	147	166	194	178	181	178	176	171	159	171	129	148	1998

Conclusions.—(i) Temperature and relative humidity alone are insufficient guides to climatic comfort in the tropics and relative humidity on its own is particularly unreliable.

(ii) An effective temperature which takes into account wind speed as well as temperature and humidity produces results which accord with local experience in Singapore.

(iii) Forced ventilation (e.g. using fans), while adequate for producing comfortable conditions at some times of the day and year, is incapable of dealing with the more extreme conditions, particularly during the months April to June whilst for optimum comfort at the height of the north-east monsoon, some form of protection against excessive wind speed or ventilation is desirable.

(iv) Staff being posted to Singapore from temperate climates would find it best to arrive in one of the 'winter' months, and in particular February, whilst Treasury inspections, to produce the optimum result, should be made in April or May!

REFERENCES

1. New York, American Society of Heating and Ventilating Engineers. Effective temperature chart showing normal scale of effective temperature. Applicable to inhabitants of the U.S. under certain conditions. *Guide, New York*, 1944, p. 61.
2. Air Ministry. Handbook of preventive medicine, A.P. 1269B. Air Ministry, London.

NOTES AND NEWS

Meteorological Magazine: increase in price

We regret that owing to further increases in the cost of printing and publication it has become necessary to raise the price of the *Meteorological Magazine*. The price will be 3*s*. 0*d*. an issue with effect from the January 1964 number. The net annual subscription will become 39*s*. including postage. Present subscribers will remain on the existing rate until renewal of their subscriptions is due.

Klimaschwankungen und Grossräumige Klimabeeinflussung, by H. Flohn. 6½ in. × 9½ in. pp. 61, Westdeutscher Verlag, 567 Opladen/Rhld, Oplovener Strasse 1–3, 1963. Price: 6 DM.

This booklet on variations of climate, both natural and artificially provoked, with English and French summaries each half a page in length, plus brief discussion, will provide a handy introduction for many to a subject of increasing and somewhat anxious importance. The work is a concise review of a field that is wider than meteorology itself, written with the authority of a leading meteorologist with an unusually wide knowledge. Its distinguishing characteristic is the attempt to provide quantitative estimates, wherever possible, of the influence of each of the many factors that affect world climate. Inevitably these are confined in some instances to mere illustration from special observations at some sample locality (usually in central Europe) and in other cases to admittedly very broad estimates. (English readers may not be familiar with two abbreviations used in Flohn's estimates: '/d' to mean 'per diem' and '/a' to mean 'per annum'). Some of the estimates may not stand the test of time. However all this is clearly stated, and the occasion used to point the need for specific further research to improve on existing knowledge.

The 75-entry bibliography, with items on radiation balance, moisture transport, general-circulation dynamics, effects of local geography, effects of volcanic eruptions and hydrogen bombs, proposals for artificially regulating the climates of the globe and resettling hundreds of millions of people, reveals the awe inspiring scope of the subject and the author's wide acquaintance with it. Only about half the papers cited are published in Germany, the remainder representing work in more than a dozen countries including the U.S.A., Russia, Britain, Israel, Japan, India, East and South Africa, Australia and South America—29 items in English, two in Russian and one in Spanish.

Flohn accords greater importance than most workers hitherto to annual bush fires in tropical lands (putting, he reckons, nearly as much carbon dioxide into the atmosphere as does industrial and domestic burning of coal and oil mainly in temperate countries) and to the change of albedo brought about when natural forest is cleared and converted to grass or crop land. The latter change has been progressing over the last 5000 years.

The author's thesis is that by now the existence of cumulative, unintended effects upon world climate resulting from the activities of man cannot be denied. Therefore the question of large-scale modification of climate must receive the attention of science. Treatment must be based upon the laws of physics and demands a quantitative theory of climate and the ('climatogenetic') processes that produce it. This goes beyond any knowledge or understanding scientists yet have, but attacks on the problem have begun from various sides, notably the mathematical concepts of the general circulation associated with Rossby, Neumann and their successors, the laboratory models of rotating fluids, due to Riehl and Fultz, and the more largely empirical work of Budyko, Wexler and others.

Several large-scale projects for the manipulation of climate have already secured serious attention. These are briefly described and reviewed by Flohn.

The "Stalin plan for the transformation of nature", and particularly the Russian engineer Davydov's scheme for diversion of Siberian rivers and formation of an inland sea have been the first of these to acquire the status more or less of government policy, though apparently things are not yet beyond the stage of instigating much research (resulting in some toning down of the expectations). Other grandiose proposals such as the artificial melting of the Arctic ice, the sealing off of the Mediterranean and the damming of the waters of the Nile at various latitudes, are briefly noticed and a suitable meteorological critique applied. In every case it is clear that scientists are not yet in a position to predict the outcome satisfactorily. At this stage therefore action is premature and likely to lead to disappointment (the Aswan dam is mentioned), if not to disastrous side effects.

H. H. LAMB

Atmospheric turbulence and its relation to aircraft, Proceedings of a Symposium held at the Royal Aircraft Establishment, Farnborough on 16 November 1961. London, Ministry of Aviation. 9½in. x 6½in., pp. iv + 287, HMSO, London, 1963. Price: 30*s*.

A considerable volume of data has accumulated in recent years regarding atmospheric turbulence. At the same time, the importance of turbulence to aircraft has increased with the advent of new types of aircraft having characteristics appreciably different from their predecessors. The reported symposium was therefore especially welcome as it brought meteorologists and aeronautical workers together and provided a valuable exchange of ideas.

The symposium was divided into two basic sections. After an introductory paper the meteorological background was first covered, then came papers which looked at aircraft response to turbulence and at the considerations which have to be paid to turbulence in regard to airworthiness of aircraft.

The introductory paper, by J. K. Zbrozek, looks at the problem as a whole. It outlines those aspects of aircraft engineering affected by turbulence and gives an engineer's view of the turbulence. The *discrete-gust* and *spectral density* methods of assessing aircraft response are discussed and examples of measured spectra are given. This paper is especially interesting to the meteorologist anxious to understand more fully the problems of the engineer.

The meteorological papers are introduced in a paper, by P. A. Sheppard, which presents a general picture of the incidence of atmospheric turbulence and gives a broad outline of the turbulence-generating processes which provides an important background for the later papers. The next paper, by T. H. Ellison, is a fundamental and provocative discussion of the mechanisms of turbulence in which some stimulating ideas are put forward regarding the effects of density gradients. In the fourth paper F. Pasquill gives a compact summary of the statistics of turbulence, in the lowest layers, considered from the spectral view-point. He presents the progress made toward a coherent description of three aspects; the shape of the high-frequency side of the spectrum, the scale and the intensity of turbulence. The effects of finite sampling are discussed.

The remaining meteorological papers consider special facets of atmospheric turbulence. Paper 5, by J. K. Bannon, summarizes existing knowledge on high-level turbulence. Paper 6, by F. H. Ludlam, presents new views on air movement inside cumulonimbus cloud and stresses the importance of wind shear. A storm is presented as a heat engine in which the efficiency is increased by organized up and down-draughts. The severity and dimensions of the draughts are discussed in relation to aircraft. Paper 7, by R. S. Scorer, considers possible mechanisms for inducing stirring motions in stably-stratified air-streams by flow over mountains. Findings of theory are supported by inference from observations and some excellent photographs of billow patterns in cloud are presented.

The aircraft side is introduced in Paper 8, by G. F. H. Hemsley. This paper looks at air turbulence in relation to aircraft design and reviews the critical effects of atmospheric conditions on structural design, fatigue life, aircraft control and performance and on aircraft equipment. Next N. I. Bullen, in a discussion of gust loads on aircraft, describes methods of measurement and of analysis. A review of available information is made and the main results summarized. In Paper 10 J. Burnham gives a study of aircraft response to turbulent air. On the limited information available he shows that load histories experienced by different aircraft are related in a way which is essentially the same for the 'discrete-gust' and 'spectral' methods of assessing response. However, before reliable estimates can be made for possible future aircraft, information is required about turbulence spectra for the long wavelengths to which these aircraft predominantly respond. Finally Paper 11, by W. Tye, reviews the applications of the knowledge of atmospheric turbulence and underlines the problems which appear to the airworthiness engineer to need the most urgent attention.

It is considered that this book is a valuable contribution to the co-ordination of understanding concerning the application of turbulence information to aircraft. Particularly useful to the reader are the reported discussions. Meteorologists should certainly get a clearer idea of the problems involved and of the ways in which workers in meteorology may be of more service to their opposite numbers in the aeronautical fields.

The book represents remarkable value for the modest price. The printing and diagrams are clear though the covers do not, unfortunately, maintain the same high standard.

J. BRIGGS

LETTER TO THE EDITOR

Complete and incomplete wind data collections

Mr. Dewar's interesting paper 'The computation of monthly summaries of winds from incomplete data', in the *Meteorological Magazine* for April 1963, compares 100-mb wind statistics from complete and incomplete data collections for three stations in England. Mr. Dewar properly hesitated to draw conclusions from his data concering comparisons at other altitudes.

In this connection, I invite attention to comparisons between five-year serially complete once-daily wind data sets, and incomplete data collections comprising all available observations for periods of at least five years, at several stations in the United States.[1] The comparisons were made between vertical profiles of the zonal mean components and their standard deviations, as derived from the incomplete and complete data sets, at a total of eighteen stations.

Differences during summer were not appreciable, but in the winter season, profiles at four stations showed biases in the 'incomplete' zonal means amounting to about 30 per cent, at and near jet stream altitudes. As a matter of possible interest, the four pairs of zonal mean wind profiles reproduced in reference 1 indicate a tendency towards minimum differences near the 100-mb level.

Winter differences in the standard deviations of the zonal components were of comparable size, but not biaises, inasmuch as the values from the incomplete data set were both larger and smaller than those from the complete wind series.

I would like to suggest that a 'missing link' of concern to analyses of this sort involves serial persistence inherent in the data. One would expect the larger magnitudes in an incomplete wind collection to be relatively statistically independent, compared to the numerous smaller values which however contain substantial statistical redundancy. This effect is not significant of course if one is describing a defined set of observations, but it might be important if one's purpose is to estimate future observations, by use of statistical inference.

Washington, U.S.A. B. N. CHARLES

REFERENCE

1. CHARLES, B. N.; On some limitations of upper wind records. *J. geophys. Res., Richmond, Va.*, **64**, 1959, p. 343.

METEOROLOGICAL OFFICE NEWS

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

Miss A. E. Murray, Experimental Officer, who retired on 11 July 1963:

Miss Murray retired after a long career in the Office, spent entirely on Climatological work. She joined the staff of the Scottish Meteorological Society in Edinburgh in 1919 and came into the Meteorological Office in April 1920, when the Office took over the work of the Society. She was transferred to M.O.3 at Harrow in October 1947. Miss Murray was most adept at dealing with masses of data involved in climatology. She once contributed regular articles to the *Glasgow Herald*; but undoubtedly her greatest contribution to the work of the Office was through her pleasant assiduity in dealing with inquirers of all types, and there is no doubt that many inquirers will miss her cheery voice, as will her colleagues in the Office.

R.H.C.

Mr. J. F. Oliver, Experimental Officer, who retired on 31 July 1963 after 44 years' service:

'Olly,' as he has been affectionately known throughout the Office, began his career as a Boy Assistant in British Rainfall Organization. Although he has served at a number of outstations, most of his time has been spent at Headquarters where he has been engaged on duties involving the staffing of outstations serving both military and civil aviation. Olly has always had the general welfare of the staff uppermost in mind and has, like others before him, spent a great deal of time and energy smoothing out the many difficulties that arise in any big organization. He will continue to help and serve others as a lay preacher in the Methodist Church. D.J.W.

Wt. 22, K16, 11/65, Gp. 1535

METEOROLOGICAL OFFICE M.O.738

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PREDICTION OF THE 24-HOUR DISPLACEMENT OF THERMAL TROUGHS

By G. R. R. BENWELL and G. A. WATT

Summary.—The 24-hour displacement of 1000–500 mb thermal troughs was examined during the period 1960–61 over the sector of the northern hemisphere from the eastern seaboard of America to western Europe. Objective forecasting techniques programmed for use on the computer METEOR were used for selection of the significant parameters for prediction of the latitude and longitude displacement. The best results were achieved by retaining eight parameters for predicting the latitudinal movement and nine parameters for predicting the longitudinal movement in the following 24 hours, with multiple correlation coefficients of 0.75 and 0.67 respectively and root mean square errors of 2.83 degrees of latitude and 4.61 degrees of longitude.

Introduction.—This investigation followed earlier work by Miles and Watt[1] on relaxing thermal troughs and by Miles[2] on amplifying thermal troughs, but it was concerned with the more general problem of predicting the magnitude of the 24-hour latitudinal and longitudinal displacement of thermal troughs. The method followed was to extract values of a large number of parameters for each occasion and to use the objective statistical methods programmed for the METEOR computer by Freeman[3] for selection of the significant parameters. The particular programme used was the multiple non-linear regression programme, also adopted by Moore,[4] which uses the method of least squares to obtain from the data a regression relation of the form:

$$z = a_0 + a_1x_1 + a_2x_1^2 + \ldots . \; b_1x_2 + b_2x_2^2 + \ldots \qquad \ldots(1)$$

The predicand z, in this case, is the latitude (or longitude) displacement of the thermal trough in 24 hours, and x_1, x_2, etc., are the parameters for which values have been extracted. The programme includes a stage for applying significance tests and finally arranges for printing out the requisite coefficients of the regression formula, and also the root mean square error of the predicted values.

The thickness line defining the thermal trough.—For the purpose of this investigation it was necessary to regard each thermal trough as defined by a particular thickness line. This line was chosen so as to extend through the region of strongest thermal gradient in the neighbourhood of the trough line on the initial chart. Subsequent measurements relate to the same line (i.e. the line with the same 1000–500 mb thickness), e.g. the latitudinal and longitudinal displacements of the trough were defined in relation to this line.

Selection of significant parameters.—Details were assembled of 503 thermal troughs during the two-year period 1960–61 and covering the sector of the northern hemisphere from the eastern seaboard of America to western Europe.

Associated synoptic features are shown in Figure 1 along with the abbreviations used in the tables in this paper. Relationships connected with these

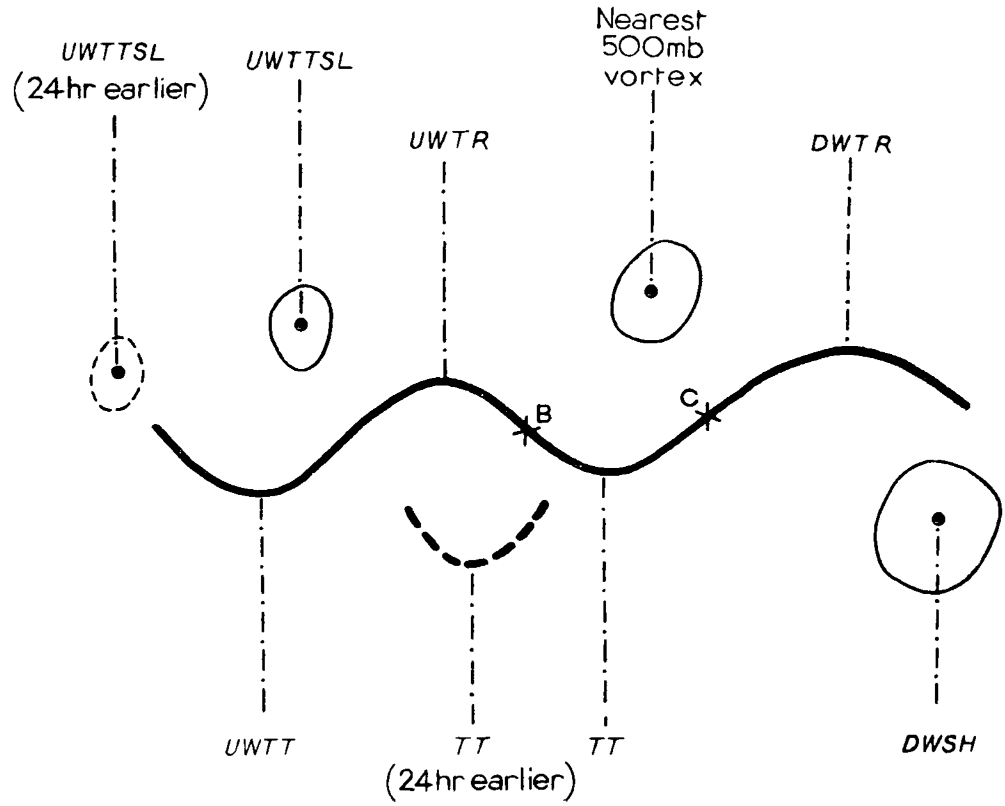

FIGURE 1—SYNOPTIC FEATURES USED IN THE INVESTIGATION

——— Thickness line defining trough
- - - - Thickness line defining trough 24 hours earlier
——— Isopleth delineating surface low, surface high or 500-mb vortex
- - - - Isopleth delineating surface low 24 hours earlier
TT Thermal trough for which prediction is required
UWTT Upwind thermal trough
UWTTSL Upwind thermal trough surface low
UWTR Upwind thermal ridge
DWTR Downwind thermal ridge
DWSH Downwind surface high

B and C are positions used for measurement of 500-mb flow where direction is measured in degrees true, and gradient in decametres per 400 nautical miles.

features were used as parameters in equation (1) for forecasting the movement of the thermal trough. Parameters are listed and numbered in Table I, and in Figures 2 and 3 the parameters found to be the most significant are shown in diagram form.

Various powers of the parameters appear in equation (1), and powers of the parameters up to the sixth were used in the initial work on latitude prediction. It was considered, however, that the size of the sample (503 cases) did

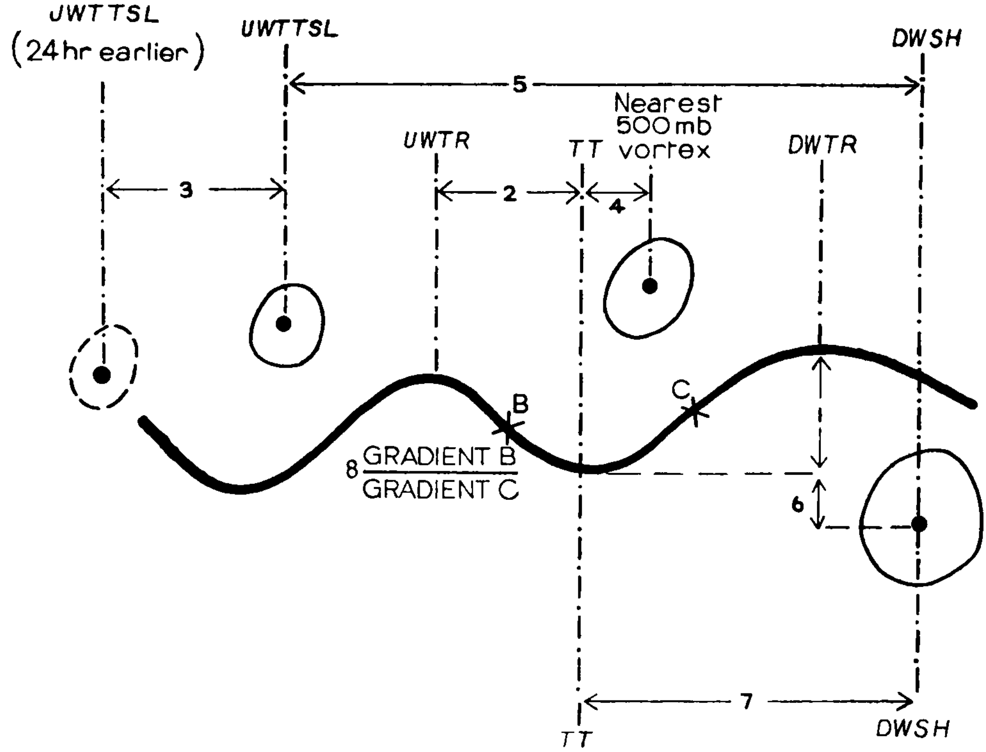

FIGURE 2—LATITUDE PREDICTION: SIGNIFICANT PARAMETERS

Parameters are numbered with reference to Table I. For abbreviations see Figure 1.

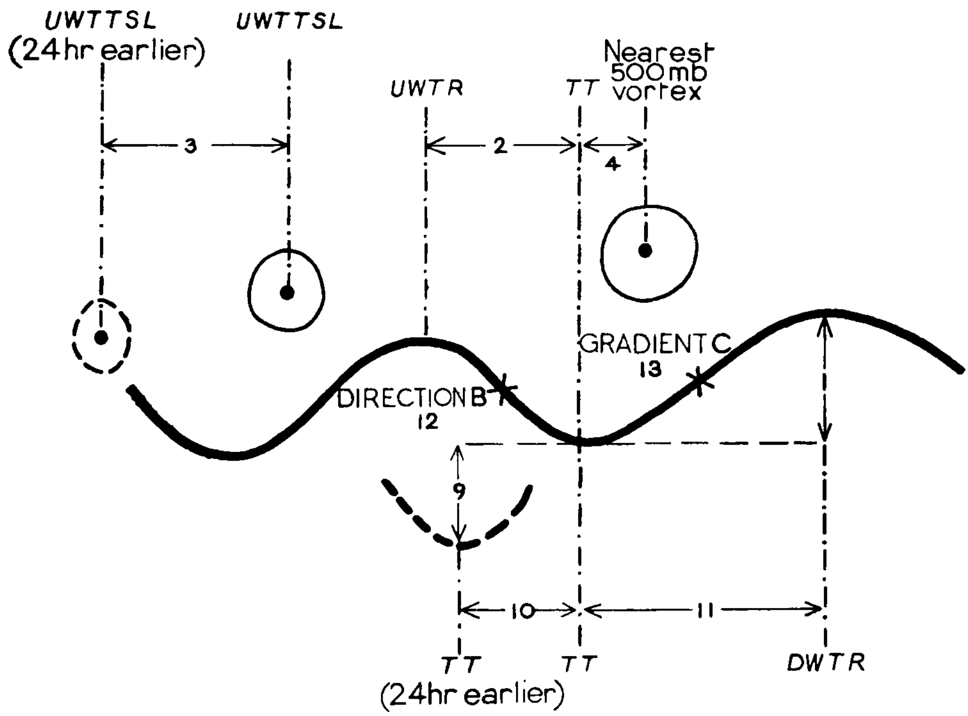

FIGURE 3—LONGITUDE PREDICTION: SIGNIFICANT PARAMETERS

Parameters are numbered with reference to Table I. For abbreviations see Figure 1.

not warrant the use of powers greater than the third, and for the rest of the work powers were restricted to powers up to the third; it is interesting to note the effect of this restraint (Table II).

TABLE I—PARAMETERS AND THEIR CORRELATIONS WITH 24-HOUR DISPLACEMENTS

	Latitude displacement		Longitude displacement	
	Correlation coefficient	Powers retained (significant parameters)	Correlation coefficient	Powers retained (significant parameters)
1. LAT SEP: *TT–DWTR*	+0.46	1,2,3	−0.11	2
2. LONG SEP: *UWTR–TT*	−0.41	2,3	−0.40	1,3
3. LONG CHANGE: *UWTTSL* last 24 hours	+0.39	2	+0.26	1
4. LONG SEP: nearest 500-mb vortex–*TT*	+0.30	1,2	0.00	1,3
5. LONG SEP: *UWTTSL–DWSH*	−0.12	1,2,3	−0.28	
6. LAT SEP: *TT–DWSH*	+0.22	2,3	−0.26	
7. LONG SEP: *TT–DWSH*	+0.16	1	−0.08	
8. 500-mb GRADIENT at B / 500-mb GRADIENT at C (i.e. confluence or diffluence ratio)	−0.28	1	−0.09	
9. LAT CHANGE: *TT* last 24 hours	+0.22		+0.40	1
10. LONG CHANGE: *TT* last 24 hours	−0.18		+0.25	2
11. LONG SEP: *TT–DWTR*	+0.04		+0.17	1,2,3
12. 500-mb DIRECTION at B	−0.14		−0.37	2
13. 500-mb GRADIENT at C	+0.17		+0.24	2
14. 500-mb GRADIENT at B	−0.16		+0.08	
15. LAT SEP: nearest 500-mb vortex–*TT*	+0.31		−0.06	
16. Central pressure *UWTTSL*	−0.04		+0.05	
17. LONG: *TT*	+0.10		+0.12	
18. LAT: *DWSH*	+0.08		−0.11	
19. MONTH	+0.07		0.00	
20. LAT SEP: *TT–DWTR* (using thickness line 6 decametres greater than defining line)	+0.52		−0.08	

LAT=latitude LONG=longitude SEP=separation
Other abbreviations are explained in Figure 1.
Note: Parameters numbered 14–20 were rejected by significance test.

TABLE II—EFFECT OF RESTRICTING POWERS OF PARAMETERS (LATITUDE PREDICTION)

Restriction in powers	Highest multiple correlation coefficient	Number of parameters retained as significant	Root mean square error *degrees*
Up to sixth	0.77	10	2.70
Up to third	0.75	8	2.83

All the parameters used in the investigation are set out in Table I and also their individual linear correlations with the 24-hour displacement in latitude and in longitude of the thermal trough. The parameters consisted of those suggested from the earlier work of Miles and Watt,[1] and of those others shown to be probably significant by a pilot scheme conducted on 300 cases. The parameters were selected if they were significant at the 5 per cent level, and the powers of the parameters retained by the programme are indicated in the table. It will also be seen from the table that the significant parameters for prediction are not necessarily those with the highest individual linear correlation coefficients.

Other parameters such as vorticity or Rossby wave speed might have been incorporated into the work, but the fact that meteorological variables are not independent and are closely correlated means that, provided the initial number of variables is sufficiently large, there is little ground for expecting appreciable improvement by extending the number of parameters indefinitely. Probably the largest source of error in this kind of work is found in the initial conditions when, as in this work, information is required for areas where data are sparse; experience suggests that the error in positioning a thermal trough over the Atlantic must be of the order of two or three degrees on many occasions.

Effect of reducing the number of significant parameters.—The multiple correlation coefficient using the eight significant parameters for latitude prediction was found to be 0.75, with a root mean square error of 2.83 degrees of latitude; using the nine significant parameters for longitude prediction, the multiple correlation coefficient was found to be 0.67 with a root mean square error of 4.61 degrees of longitude. The effect of using fewer parameters is shown in Table III which gives the multiple correlation coefficients and root mean square errors obtained for smaller sets of parameters. Each set was obtained by choosing the parameters so that the best combination was obtained for that size of set.

TABLE III—EFFECT OF REDUCING THE NUMBER OF SIGNIFICANT PARAMETERS

Number of parameters	Latitude displacement: Multiple correlation coefficient	Latitude displacement: Root mean square error *degrees*	Longitude displacement: Multiple correlation coefficient	Longitude displacement: Root mean square error *degrees*
9	—	—	0.67	4.61
8	0.75	2.83	0.65	4.73
7	0.72	2.94	0.64	4.77
6	0.70	3.04	0.63	4.82
5	0.67	3.14	0.61	4.92
4	0.66	3.18	0.57	5.11
3	0.64	3.26	0.54	5.26

Checking the results.—The method often followed in this form of investigation is to use only a part of the assembled data for the first analysis, then to modify the results by incorporating a second part of the data and finally to use the rest of the assembled data in a check of the method. In this investigation it was decided to use all the assembled data in selecting the significant parameters; to obtain an estimate of the variability of the results in practice, the 503 cases were split in various ways and the multiple correlation coefficients and root mean square errors resulting from the use of the significant parameters were obtained for each sample. These results are shown in Table IV and it will be noted that the multiple correlation coefficient ranged from 0.68 to 0.80 for latitude prediction and from 0.63 to 0.70 for longitude prediction: the

TABLE IV—VARIATION WITHIN THE 503 CASES

Sample	Latitude: Correlation coefficient	Latitude: Root mean square error *degrees*	Longitude: Correlation coefficient	Longitude: Root mean square error *degrees*	Longitude: Mean change in 24 hours *degrees*
First 250 cases	0.72	2.85	0.67	4.36	11.3
Last 253 cases	0.80	2.63	0.68	4.64	13.4
First 150 cases	0.68	3.15	0.63	4.16	11.3
Last 353 cases	0.79	2.62	0.70	4.65	12.9
Cases in 1960	0.73	2.82	0.69	4.42	11.8
Cases in 1961	0.80	2.63	0.68	4.62	13.4

appropriate range of the root mean square errors was from 3.15 to 2.62 degrees for latitude prediction and from 4.16 to 4.65 degrees for longitude prediction.

The root mean square errors in the longitude prediction suggest that the samples concerned were different in character, and the measure of the mean longitudinal movement of the troughs in the different samples should also be considered. It appears that the errors are smaller for the groups in which the mean change in longitude is smaller.

It might be advisable to point out that in the latitude band 40°–60°N, 4.6 degrees of longitude is equivalent to about the same distance as 3.3 degrees of latitude. Thus the disparity between root mean square errors for latitude and longitude is not as large as at first appears.

Forecasting.—Tables V and VI may be used for forecasting; in practice the values of each of the various significant parameters would be written down after selecting the defining thickness line (the thickness line centred through

TABLE V—LONGITUDE PREDICTION

Contribution in degrees

Degrees of CHANGE or SEPARATION	LAT SEP: *TT–DWTR*	LONG SEP: *UWTR–TT*	LONG CHANGE: *UWTTSL* last 24 hours	LONG SEP: nearest 500-mb vortex–*TT*	LAT CHANGE: *TT* last 24 hours	LONG CHANGE: *TT* last 24 hours	LONG SEP: *TT–DWTR*	500-mb DIRECTION at B *degrees true*	Contribution in degrees	500-mb GRADIENT at C (decametres per 400 n.miles)	Contribution in degrees
−30				2.2							
−25				2.0							
−20				1.8							
−15				1.4							
−10			−1.4	1.0	−2.4			240	4.3	9	0.3
− 5			−0.7	0.5	−1.2		−2.0	250	3.8	12	0.5
0	5.2		0.0	0.0	0.0	0.0	0.0	260	3.3	15	0.7
5	5.1		0.7	−0.5	1.2	0.1	1.3	270	2.7	18	1.0
10	4.7	5.6	1.4	−1.0	2.4	0.5	2.1	280	2.2	21	1.4
15	4.1	3.5	2.2	−1.4	3.7	1.0	2.5	290	1.6	24	1.9
20	3.3	1.7	2.9	−1.8		1.8	2.7	300	1.0	27	2.3
25	2.2	0.1	3.6	−2.0		2.9	3.0	310	0.4	30	2.9
30	0.9	−1.2	4.3	−2.2		4.1	3.4	320	−0.2	33	3.5
35		−2.1	5.1	−2.2		5.6	4.2	330	−0.9	36	4.2
40		−2.6		−2.1		7.3	5.5	340	−1.5	39	4.9
45		−2.5		−1.8		9.3	7.6	350	−2.2	42	5.7
50				−1.4			10.6	360	−2.9	45	6.5
55				−0.8							
60				0.2							
65				1.3							
70				2.8							

Northward and eastward displacements and changes in 24 hours are positive; separations are positive if northward or eastward travel is involved in passing from the first mentioned feature to the second. A positive predicted value therefore indicates northward displacement in the case of latitude and eastward displacement in the case of longitude.

Abbreviations are explained in Figure 1 and Table I.

TABLE VI—LATITUDE PREDICTION

Contribution in degrees

Degrees of CHANGE or SEPARATION	LAT SEP: *TT–DWTR*	LONG SEP: *UWTR–TT*	LONG CHANGE: *UWTTSL* last 24 hours	LONG SEP: nearest 500-mb vortex–*TT*	LONG SEP: *UWTTSL–DWSH*	LAT SEP: *TT–DWSH*	LONG SEP: *TT–DWSH*	Confluence or diffluence ratio per cent	Contribution in degrees
−30				−3.7				40	−9.8
−25				−2.9		4.0		45	−9.9
−20				−2.2		2.4		50	−10.0
−15				−1.6		1.2		55	−10.1
−10			0.3	−1.0		0.5		60	−10.2
−5			0.1	−0.5		0.1		65	−10.4
0	0.0		0.0	0.0		0.0	0.0	70	−10.5
5	2.7	−0.2	0.1	0.4		0.1	0.4	75	−10.6
10	4.1	−0.9	0.3	0.7		0.3	0.8	80	−10.7
15	4.8	−1.7	0.6	1.0	5.5	0.6	1.2	85	−10.8
20	5.3	−2.7	1.1	1.2	6.7	0.9	1.6	90	−11.0
25	5.9	−3.6	1.8	1.4	7.7	1.1	2.0	95	−11.1
30	7.1	−4.3	2.6	1.5	8.4	1.2	2.4	100	−11.2
35		−4.8	3.5	1.5	9.0	1.0	2.8	105	−11.3
40		−4.7		1.5	9.3	0.6	3.2	110	−11.4
45		−4.1		1.4	9.4		3.6	115	−11.6
50				1.3	9.4		4.0	120	−11.7
55				1.1	9.3		4.4	125	−11.8
60				0.8	9.0		4.8	130	−11.9
65				0.4	8.6		5.2	135	−12.1
70				0.0	8.1		5.6		
75					7.5		6.0		
80					6.9		6.4		
85					6.3		6.8		
90					5.7				
95					5.1				
100					4.5				
105					4.0				
110					3.6				
115					3.2				
120					3.0				
125					2.8				
130					2.8				
135					3.0				

Northward and eastward displacements and changes in 24 hours are positive; separations are positive if northward or eastward travel is involved in passing from the first mentioned feature to the second. A positive predicted value therefore indicates northward displacement in the case of latitude and eastward displacement in the case of longitude.

Abbreviations are explained in Figure 1 and Table I.

the strongest gradient in the thermal trough). Reference to the appropriate tables would give the contribution to the displacement for each parameter and the sum total would give the predicted displacement.

The convention used for sign in this investigation is that northward and eastward displacements and changes in 24 hours are positive; separations are positive if northward or eastward travel is involved in passing from the first mentioned feature to the second. A positive predicted value therefore indicates northward displacement in the case of latitude and eastward displacement in the case of longitude.

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551.551:551.558.21

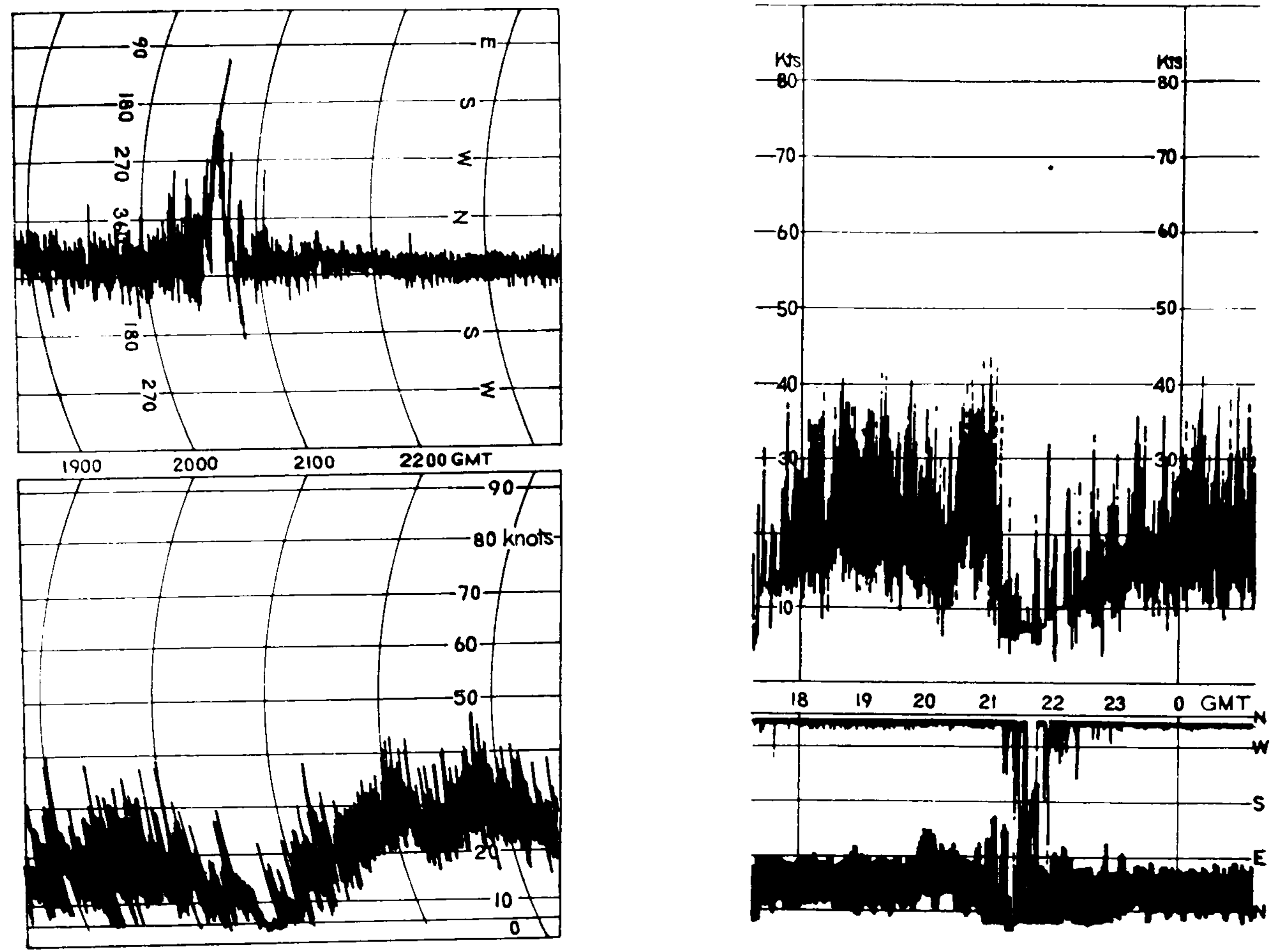
ROTOR STREAMING OVER THE PENNINES

By L. DENT and B. DYSON

A period of unusually severe surface turbulence occurred in east Cheshire on the evening of 31 December 1962 and continued into 2 January 1963. Unpleasant flying conditions were reported near Manchester Airport. At Macclesfield the Cheshire Fire Service received over 300 calls for assistance between these dates to deal with damaged property, ranging from the collapse of chimney stacks and removal of a house roof to uprooted trees, one of which killed a motorist. Calls increased rapidly after 1500 GMT and reached a peak between 2100 and 2200 GMT on New Year's Eve.

Aircraft reports.—Aircraft operating into Manchester Airport reported severe turbulence on 31 December. A BEA Viscount landed at 2035 GMT from London after suddenly encountering violent turbulence at 5500 feet over Congleton. The pilot was lifted from his seat for several seconds, whilst a passenger was flung against the roof of the aircraft and received head injuries. Descending with indicated airspeed of 155 knots, 43 per cent flap, and power off, i.e. throttles back, the aircraft reached 3200 feet only to be lifted back to 4800 feet. The turbulence during descent was described as varying between moderate and violent, the initial impact over Congleton being worst.

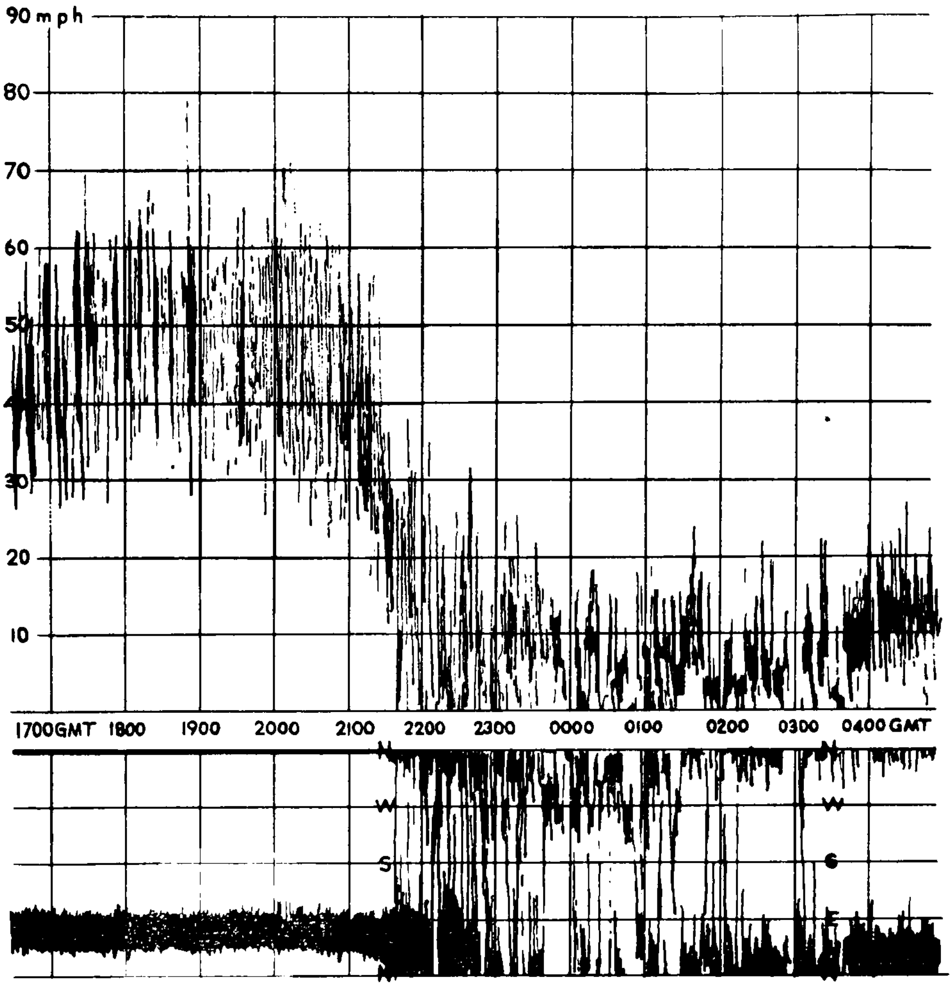
Another BEA Viscount landed at 1920 GMT from Birmingham after meeting severe clear air turbulence over Congleton at 6000 feet. With wheels down and 43 per cent flap, fluctuations in indicated airspeed between 130 and 170 knots were common. At 2000 GMT taking off on runway '06' towards the hills at Oldham, this same aircraft met with only moderate turbulence which ceased above 6000 feet. Route weather at 17,000 feet on this flight between Glasgow and Birmingham was reasonably smooth. Finally landing at 2330 GMT turbulence was again encountered near Congleton, but was less severe than on the previous occasion. There was a little cloud up to 8000 feet on the final flight but no significant cloud earlier. South of Congleton at 6000 feet turbulence was not remarkable.



(*a*) Manchester Airport

(*b*) Jodrell Bank

FIGURE 1—ANEMOGRAMS FOR 31 DECEMBER 1962 TO 1 JANUARY 1963



(*c*) Macclesfield Sewage Works

FIGURE 1—ANEMOGRAM FOR 31 DECEMBER 1962 TO 1 JANUARY 1963 (*contd*)

Anemograms.—Figure 1 (*a*), (*b*) and (*c*) are copies of anemograms for 31 December 1962 to 1 January 1963 from Manchester Airport, Jodrell Bank and Macclesfield Sewage Works at Prestbury respectively. The most noteworthy record is for Prestbury where the wind increased to 50 mph with gusts to near 80 mph after 1700 GMT on 31 December and then fell off sharply at 2130 with the sudden onset of a rapidly varying wind direction. This disturbance was maintained until about 1700 GMT, 1 January 1963 after which the gusty easterly wind was resumed. During the first six hours the direction was quite erratic, but after about 0400 it was mainly limited to south-east through north to north-west.

At Manchester Airport the easterly wind was interrupted for a short while at 2030 GMT on 31 December when the speed fell to below 10 knots with a variable direction, and at one point a calm. A similar feature is seen on the Jodrell Bank anemogram about 2115. At Manchester Weather Centre the gusty easterly wind was maintained throughout the night but a noticeable temporary moderation occurred at 1900 GMT.

Synoptic details.—The hourly surface synoptic charts from 1500 GMT on 31 December 1962 to 0001 1 January 1963 represent a strong easterly gradient of 100° at 40–50 knots over northern and central England. Extensive strato-cumulus cloud gave occasional light snow or freezing drizzle in places though not at Manchester. Pressure rose throughout the period of these charts but by 2100 GMT on 31 December a lee trough was forming to the west of the southern Pennines, and at 2300 a small centre could be sketched in to the south of Manchester. An occlusion was almost stationary from Cork to Dorset and was associated with a westerly thermal wind in the 1000–500-millibar layer over England which reduced the strong easterlies below the inversion to light winds aloft.

Rotor streaming.—The severity of the turbulence, and the anemograms together with the wind and temperature data suggest that the strange behaviour of the wind on New Year's Eve was due to rotor streaming over the Pennines. The absence of any supporting visual observations because it was dark makes it difficult to deduce the organization of the rotor.

The phenomenon of wave streaming has been reported from the Isle of Man by F. W. Ward[1] and from Crossfell in Cumberland by G. Manley[2] but there are probably few instrumental records made in rotor streaming. Corby[3] has described this extreme feature of mountain airflow and quotes the work of the Czech glider pilot Förchtgott. Figure 2 is taken from *Meteorological Report No.* 18[3] and illustrates the mechanism. The essential ingredients appear to be

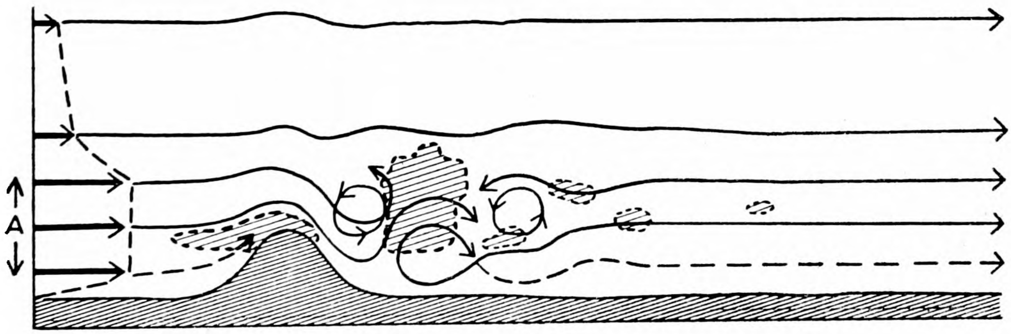


FIGURE 2—ROTOR STREAMING (AFTER FÖRCHTGOTT[3])

'A' indicates streaming layer. Bold arrows on the left show the wind profile.

a strong wind component across the mountain ridge—on the present occasion winds were easterly—together with a reverse wind shear which reduces this component to a low value at some higher level, so providing a streaming layer of limited depth.

An examination of the temperature and wind data for the undisturbed airstream over Hemsby at 1200 GMT on 31 December reveals a marked temperature inversion between 870 and 820 mb above which the 30-knot easterly wind fell off to 12 knots at 800 mb. Figure 3 shows this variation of temperature and wind with height together with the profile of Scorer's parameter l^2. These

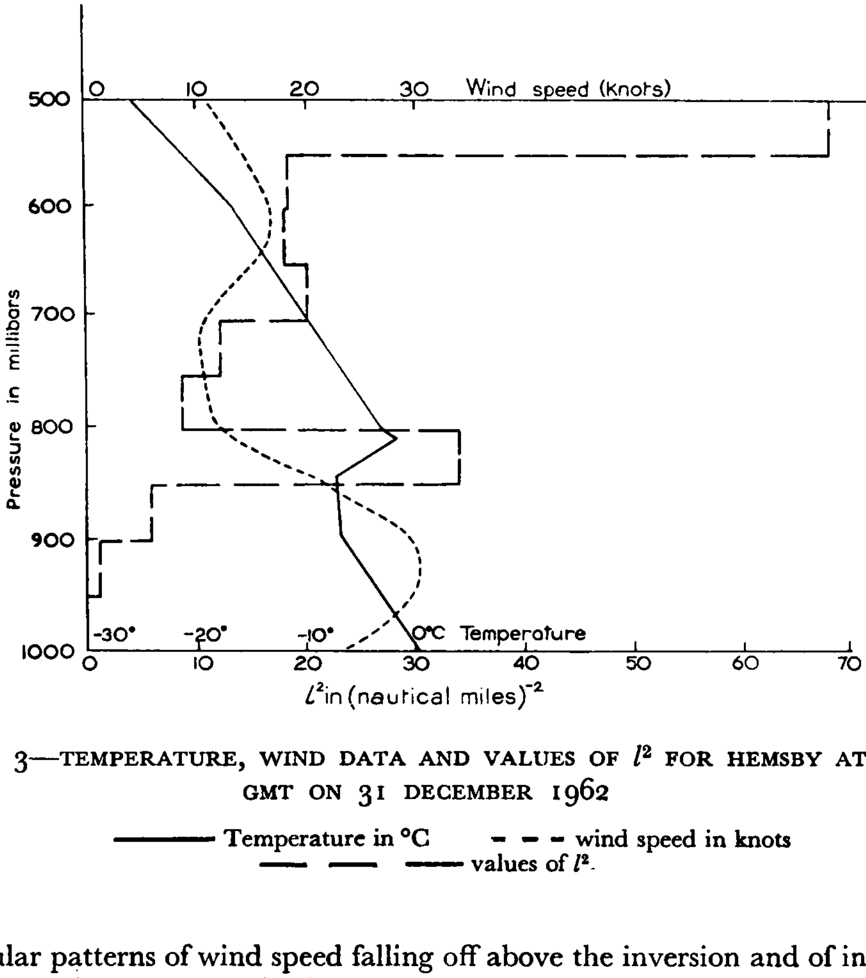


FIGURE 3—TEMPERATURE, WIND DATA AND VALUES OF l^2 FOR HEMSBY AT 1200 GMT ON 31 DECEMBER 1962

——— Temperature in °C   - - - wind speed in knots
—— —— —— values of l^2.

particular patterns of wind speed falling off above the inversion and of increasing values of l^2 are precisely those specified by Corby for rotor streaming and severe turbulence. The example fits very closely to the Förchtgott model. The turbulence occurred in a layer exactly three times the height of the offending mountain, probably Shining Tor and its neighbouring ridges shown in Figure 4.

Acknowledgements.—The authors are indebted to the Director, Nuffield Radio Astronomy Laboratories, Jodrell Bank for the loan of Figure 1 (*b*) and to the Manager, Macclesfield Sewage Department for the loan of Figure 1 (*c*).

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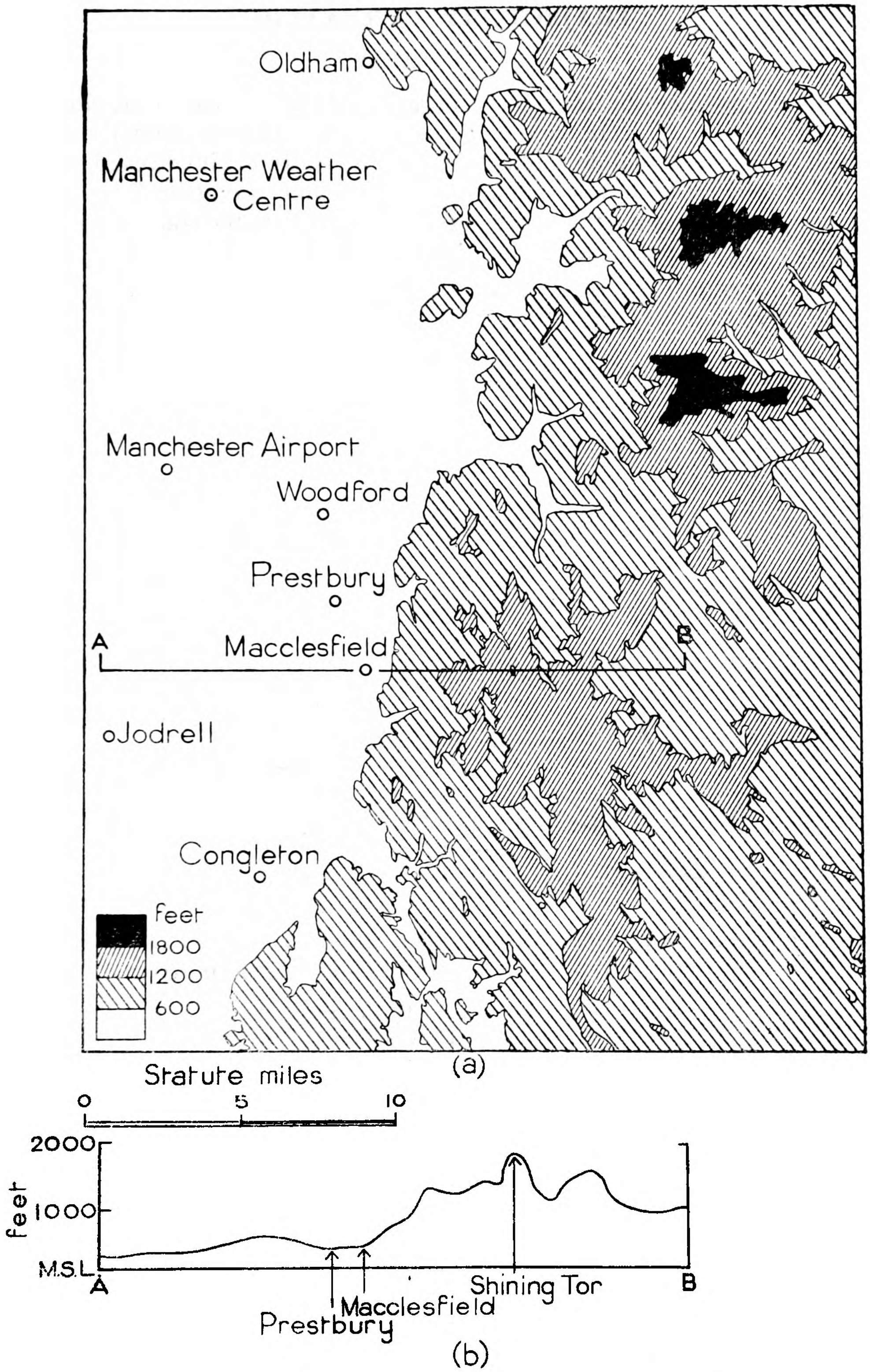

FIGURE 4—TOPOGRAPHICAL FEATURES OF THE AREA

(*a*) Relief map

(*b*) Cross-section through AB

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TRAJECTORY CURVATURE

By J. C. SAXBY

In synoptic practice the trajectory curvature of an air particle is calculated in order to use the gradient wind equation as a better estimate than the geostrophic. The conventional formula used for this purpose involves the use of contour curvature as an approximation to streamline curvature. The equation now proposed relates the trajectory curvature directly to the contour curvature.

Using vector notation, if a contour OC (Figure 1) is moving with velocity **c** in the direction OD, an air particle at O with velocity **v** in the direction

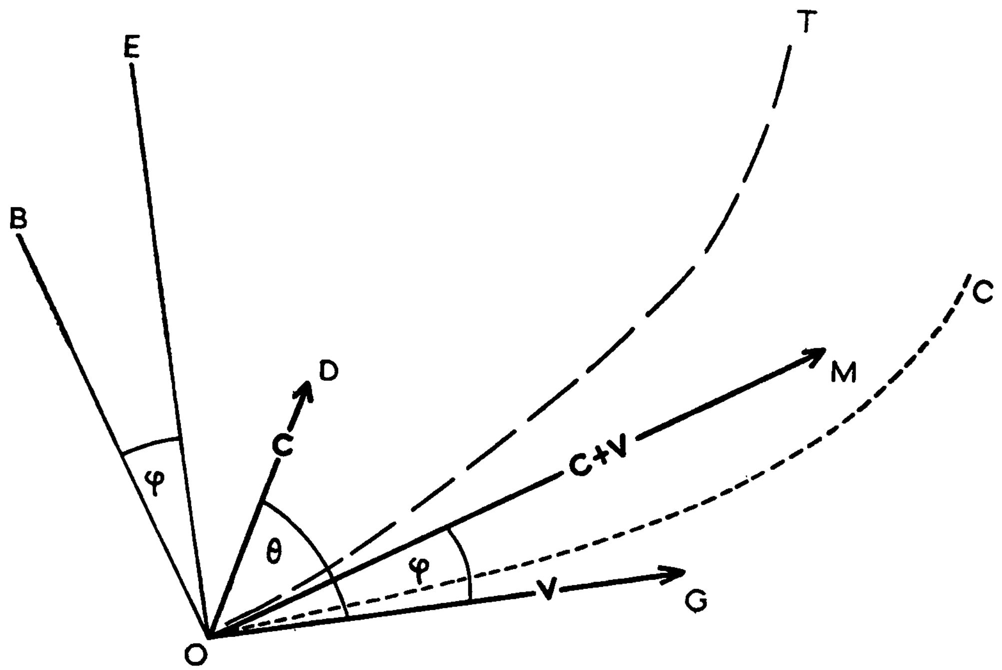


FIGURE 1—THE PARALLELOGRAM OF VELOCITIES AND THE ANGLE φ BETWEEN THE NORMALS TO THE CONTOUR AND THE TRAJECTORY

O — — — T Trajectory
O - - - - - C Contour

OG tangential to the contour, will describe a trajectory OT with velocity (**c** + **v**) in a direction OM tangential to the trajectory. Let the angle between **c** and **v** be θ, and the angle between (**c** + **v**) and **v** be φ.

Now the component of acceleration of the particle along OB, normal to the trajectory, is $|\mathbf{c} + \mathbf{v}|^2/r'$, where r' is the radius of curvature of the trajectory, and the modulus $|\mathbf{c} + \mathbf{v}|$ denotes the magnitude of the vector sum, i.e. $\sqrt{(c^2 + 2vc \cos \theta + v^2)}$. But the acceleration of the particle is also $\mathrm{d}(\mathbf{c} + \mathbf{v})/\mathrm{d}t$ and this is equal to $\mathrm{d}\mathbf{v}/\mathrm{d}t$ if **c** is constant in magnitude and direction. Now, $\mathrm{d}\mathbf{v}/\mathrm{d}t$ is composed of $\mathrm{d}v/\mathrm{d}t$ along the contour and v^2/r normal to the contour, (i.e. along OE) where r is the radius of curvature of the contour. The former component vanishes if v is constant. Thus the component along OB normal to the trajectory is $(v^2/r) \cos \varphi$.

Photograph by Michael Fairclongh

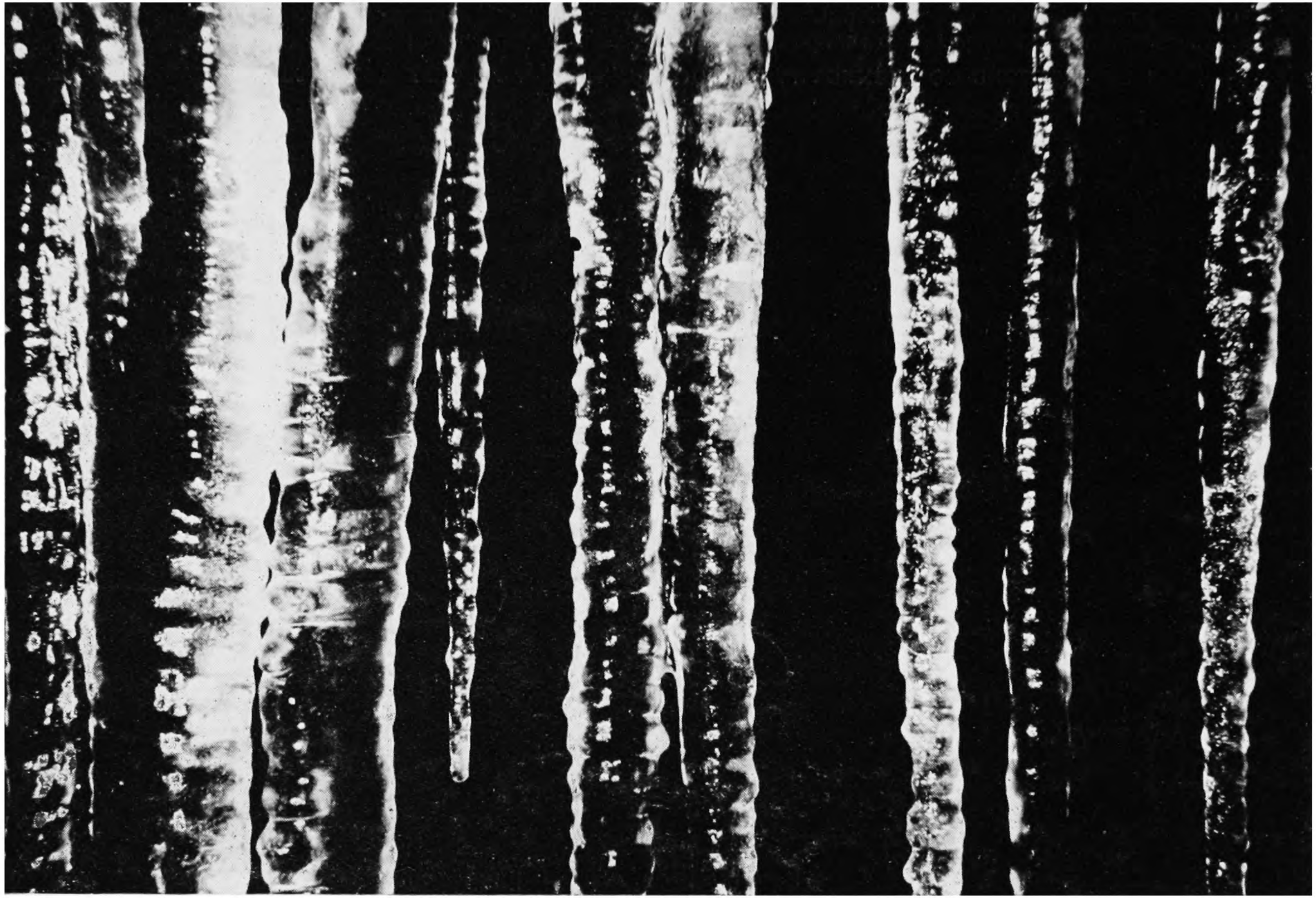
PLATE I—DAMAGE CAUSED BY THE TORNADO IN THE VALE OF YORK ON 25 JUNE 1963

See page 366

Photograph by Michael Fairclough

PLATE II—DAMAGE CAUSED BY THE TORNADO IN THE VALE OF YORK ON 25 JUNE 1963

See page 366



Photograph by M. M. Woods

PLATE III—ICICLES PHOTOGRAPHED ON THE EVENING OF 24 JANUARY 1963

Electronic flash was used to take this photograph through an open fanlight. The icicles, hanging from the roof guttering, were about three feet long.

To face p. 365

Photograph by R. K. Pilsbury

PLATE IV—THREE STAGES IN THE LIFE OF A FUNNEL CLOUD AT BRACKNELL ON 2 SEPTEMBER 1963

The photographs were taken (from left to right) at 1228, 1230 and 1236 GMT. The funnel cloud was observed in the unstable air near the centre of a shallow depression which moved over Bracknell on 2 September 1963. The depression was first located as a tropical storm (BEULAH) near the Windward Islands on 21 August.

Therefore $|\mathbf{c} + \mathbf{v}|^2/r' = (v^2/r) \cos \varphi,$ ...(1)

and hence $\dfrac{r}{r'} = \dfrac{v^2}{|\mathbf{c} + \mathbf{v}|^2} \cos \varphi.$ ...(2)

By projecting OM along OG we have, since GM = OD

$$|\mathbf{c} + \mathbf{v}| \cos \varphi = v + c \cos \theta. \qquad \ldots(3)$$

Eliminating cos φ from equations (2) and (3)

$$\frac{r}{r'} = \frac{v^2 (v + c \cos \theta)}{|\mathbf{c} + \mathbf{v}|^3}. \qquad \ldots(4)$$

The magnitude of the geostrophic wind G can be written, using vector notation,

$$G = |\mathbf{c} + \mathbf{v}| \pm \frac{|\mathbf{c} + \mathbf{v}|^2}{fr'}, \qquad \ldots(5)$$

where f is the Coriolis parameter.

Using equation (4) this becomes

$$G = |\mathbf{c} + \mathbf{v}| \pm \frac{v^2 (v + c \cos \theta)}{fr\,|\mathbf{c} + \mathbf{v}|}, \qquad \ldots(6)$$

from which tables of correction to geostrophic wind can be computed conveniently (using + sign for cyclonic curvature). The corrections are compared in Tables I and II with those recently[1] computed from the conventional formula where allowance is also made for movement of contours.

TABLE I—EXAMPLES OF CORRECTIONS TO GEOSTROPHIC WINDS FOR CONTOURS WITH CYCLONIC CURVATURE AND IN LATITUDE 50 DEGREES

G	c	θ	r	Correction	Conventional correction
knots	*knots*	*degrees*	*n. miles*	*knots*	*knots*
80	35	150	1000	−20	−15
95	15	10	500	−18	−21
130	25	145	500	−49	−45
140	30	60	1000	−24	−27
160	20	60	500	−49	−52
185	30	0	1000	−36	−41

TABLE II—EXAMPLES OF CORRECTIONS TO GEOSTROPHIC WINDS FOR CONTOURS WITH ANTICYCLONIC CURVATURE AND IN LATITUDE 50 DEGREES

G	c	θ	r	Correction	Conventional correction
knots	*knots*	*degrees*	*n. miles*	*knots*	*knots*
25	10	60	900	1	2
40	20	30	900	1	3
40	35	150	1000	20	10
65	15	10	900	10	15
90	30	0	1000	12	24
95	30	60	1000	24	43

Acknowledgement.—Acknowledgement is made to Dr. J. Pepper for detailed and critical comments on earlier drafts.

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551.515.32:551.556.1

A TORNADO IN THE VALE OF YORK ON 25 JUNE 1963

By J. HOUSEMAN

At about 1500 GMT on the grey, rainy afternoon of 25 June 1963 a disturbance, popularly described as a 'freak whirlwind,' crossed the town of Thirsk, in the Vale of York, from south to north leaving a narrow trail of damage behind.

One man was injured when he was lifted into the air and thrown against a wall about ten yards away, but otherwise damage was confined mainly to buildings and trees. Several trees were blown down, most of them falling towards the north-east; others had branches, even large limbs, torn off. One had the whole top removed, a little above the main fork in the trunk, some ten feet above the ground. The splintered ends of the torn branches distinctly show that they were twisted off. Numerous roofs were holed, slates and tiles being scattered in all directions and even heavy ridge stones thrown down. One outhouse roof was lifted, turned back to front and then replaced on its supporting walls. Part of a gable end was torn out and, in the cemetery, several gravestones were uprooted and moved for distances of up to fifty yards.

The trail of damage was about a mile long, slightly curved, with a mean direction of 350 degrees. It is difficult to estimate the width as the damage was intermittent, some objects apparently in direct line being untouched. At one point a gap 15 yards wide was made through a shelter belt of trees but, as this belt is at an angle to the line of damage the actual width of the trail is calculated at between 5 and 10 yards only. The direction of motion was from the southern edge of the town to the north-western edge. The initial development and final disappearance of the disturbance, both of which occurred in open country, were not observed (see Plates I and II).

Eyewitnesses described the phenomenon as a 'black cone' making a loud noise and this description, coupled with the character of the damage, shows fairly definitely that the disturbance was a tornado, though apparently only a small one.

No thunder was observed but there was a period of very heavy rain at the time of the passage of the tornado. The total rainfall recorded for the day at Thirsk Grammar School, which was the first building to be damaged, was 16.3 millimetres, but it is not known how much of that fell at the appropriate time. However at the Meteorological Office at Royal Air Force, Topcliffe, some two miles south-west of the school, 10 millimetres fell in the forty minutes between 1430 and 1510 GMT. When this heavy fall began rain had already been continuous for seven hours; afterwards it became slight and intermittent.

No tornado was seen from Topcliffe and there was no wind at all at the time. Earlier the wind had been blowing from 130 degrees at 10 to 15 knots and later it gradually picked up again to 10 to 15 knots from the south-west, veering north-west between 1600 and 1700 GMT. Autographic instruments recorded a sudden fall of pressure of one millibar at 1530 GMT accompanied by a temperature rise of nearly two degrees Celsius and a drop in humidity.

The synoptic charts for that day show a depression off north-west Scotland and a vigorous secondary moving north-eastwards across England. The tip of the warm sector of this secondary appears to have crossed the Thirsk area between 1500 and 1600 GMT the lowest observed pressure being 987 millibars.

The tornado seems to have formed in the unstable warm air, near the tip of the warm sector and just ahead of the depression centre, a position which Lamb[1] has stated as being a favoured situation for tornado formation.

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551.515.827:551.555.4

KATABATIC WINDS AT ACKLINGTON DURING A VERY COLD SPELL

By J. B. McGINNIGLE

During the period from 22 February 1963 until 4 March 1963, exceptionally large diurnal temperature ranges were reported in most parts of England. At Acklington, Northumberland, diurnal ranges of 12 to 16°C were noted in association with cloudless conditions and a completely snow covered ground surface. Throughout the period a katabatic wind was recorded every night.

Synoptic situation.—The synoptic situation was remarkably repetitive during the investigation period. Anticyclonic centres were maintained over Europe and Scandinavia, with intense depressions tracking south-west to north-east over the Atlantic to become slow moving in the Atlantic somewhere west or south-west of Iceland. The frontal systems associated with these depressions progressed quickly eastwards to become slow moving near Ireland.

During the period, five such systems moved in from the Atlantic. The first four became slow moving over or to the west of Ireland, each one frontolysing a little further east than the last in the following positions: 15°W (1800 GMT 24 February); 13°W (1200 GMT 27 February); 12°W (0001 GMT 1 March) and 8°W (1800 GMT 3 March). The final system moved across north-eastern England at 1800 GMT on 4 March, when the anticyclonic system, by this time over Germany, had sufficiently decayed.

The upper air structure, taken from the Aughton upper air ascents showed a typical anticyclonic, subsiding air mass. At 0001 GMT on 23 February, the subsidence inversion was 2°C in the layer 790–750 mb, the air from the surface to the inversion showing conditional instability. The air was appreciably drier above the inversion. The inversion gradually lowered and the air became drier until at 0001 GMT on 2 March, the time of maximum anticyclonic development, the base of the inversion had lowered to 1000 mb. Thereafter the anticyclonic decay showed on the ascents as a gradual cooling and moistening between 1000 and 500 mb. The anticyclonic situation was responsible for the existence of exceptional cloudless conditions over the investigation period. Of the total number of observations considered, only 12.2 per cent reported cloud below 25,000 feet.

Situation and topography.—Acklington—position 55°18′N 01°38′W, and 138 feet above mean sea level—is situated 3 miles west of the Northumberland coast in north-east England and about 1 mile south-east of the course of the River Coquet. Figure 1 shows the significant topography of the area. The ground rises slowly to the west, reaching a maximum of 1447 feet at Tosson Hill, some 13 miles away, while the Cheviot Hills, 22 miles north-west of

Acklington, rise to a maximum of 2576 feet. The source region and upper reaches of the River Coquet lie in the valley between the Cheviots and Tosson Hill.

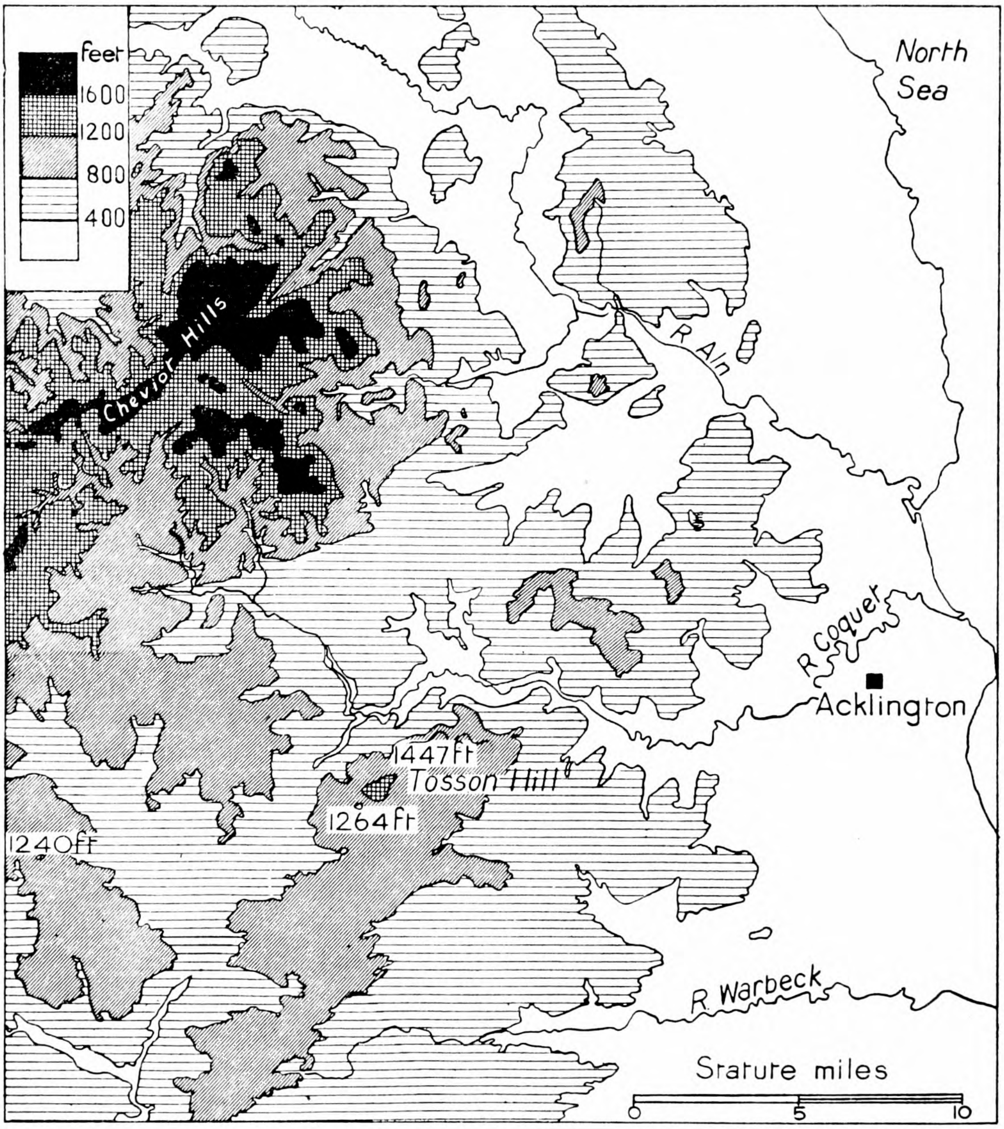

FIGURE 1—RELIEF MAP OF THE ACKLINGTON AREA

Observational data.—The period of investigation commenced at 1800 GMT on 22 February 1963 and continued until 1500 GMT on 4 March 1963. Continuous hourly observations were taken over the period, producing a total of 238.

The wind speed and direction, and air temperature for each hour were plotted for each day as in Figure 2, using a common time-axis. The gradient wind speed and direction was estimated to the nearest 5 knots and 10 degrees, using the geostrophic wind obtained from six-hourly surface synoptic charts and, where necessary, applying a correction evaluated from the gradient wind equation. The calculated wind was then checked as far as possible with the actual wind between 2000 and 3000 feet taken from the Aughton ascent.

The gradient wind so obtained was superimposed on the surface wind diagram as in Figure 2. Sunrise and sunset times were noted on the time axis.

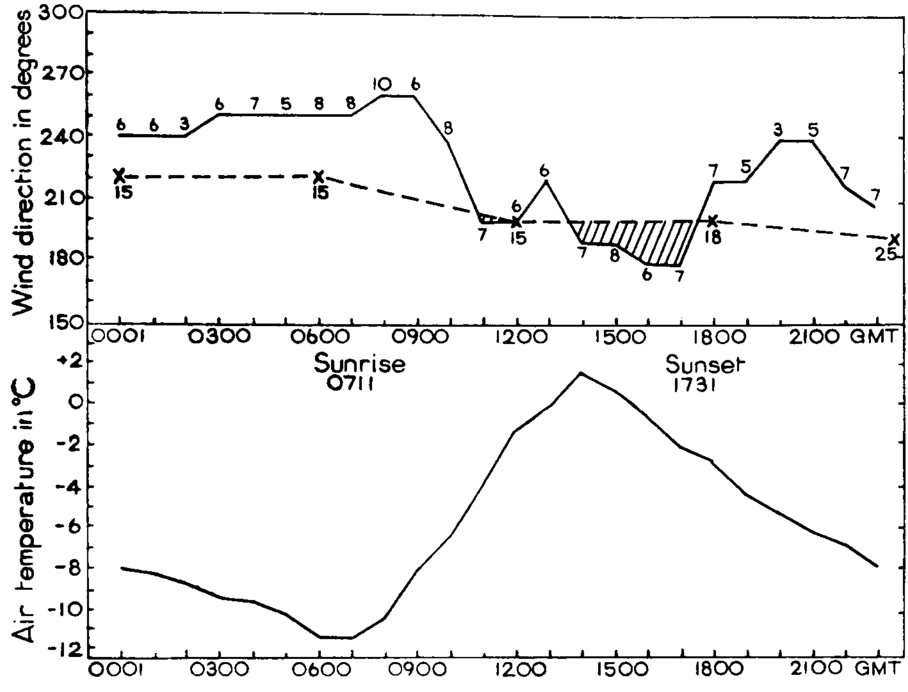

FIGURE 2—SURFACE WIND DIRECTION AND SPEED, TEMPERATURES AND ESTIMATED GRADIENT WIND ON 24 FEBRUARY 1963

In wind diagram: ———— surface wind — — — gradient wind
The figures plotted against the surface wind curve are the wind speeds recorded at that time, figures on the gradient curve are estimated speeds in knots.

Any surface wind which was veered 10° or more from the gradient wind direction was considered to be katabatic or the resultant of a katabatic flow and a normal surface wind. The onset of such a flow was always accompanied by a marked fall in air temperature, often representing the largest temperature fall of the night. Clear sky conditions were experienced throughout almost the whole period and this, with a full snow cover, was responsible for very large diurnal temperature ranges. The temperature graph in Figure 2 is typical. In addition, the observed katabatic winds were noted to be subject to fluctuation of the type which can be seen from Figure 2 during the hours 0900 to 1400 GMT. At 1100 and 1200 GMT, the katabatic wind was replaced by a surface wind of 200°. The shaded portion of the diagram shows the only time when the surface wind was not influenced by a katabatic flow.

Direction and fluctuation of the katabatic flow.—Throughout the period of investigation, a katabatic wind flow was observed every night. Of the 238 observations studied, 133 were undoubtedly katabatic winds or winds into which a katabatic component had been introduced. This figure represents 55.9 per cent of the total.

When the gradient wind was calm or south to south-westerly, less than 15 knots, the katabatic flow was from 240–270°, with a speed of 5–10 knots. This is the normal direction from which a pure katabatic flow is reported at Acklington and the following mechanism is suggested: after sunset (varying from 1729 to 1748 GMT over the period), rapid cooling takes place on the slopes of the Cheviots and on Tosson Hill, and a katabatic flow commences. The air flowing south and south-eastwards from the Cheviots joins with the air flowing north from Tosson Hill and the whole is channelled along the valley of the River Coquet, being further strengthened by the pure katabatic flow eastwards from Tosson Hill. Thus, as the flow continues along the general direction of the River Coquet, a katabatic wind of 240–270° is experienced at Acklington.

When the gradient wind was greater than 20 knots, the surface wind direction was the resultant of the pure katabatic flow and the normal surface wind direction, and therefore became more southerly as the gradient wind speed increased.

A gradient wind speed of 20–30 knots produced a resultant surface flow from 210–240° (5–10 knots). This can be seen from Figure 2, 1800–2300 GMT. A gradient wind speed of 35–40 knots produced a resultant surface wind from 190–210°. These observed directions are confirmed by the resultants obtained from vector diagrams. It was a significant fact that when the gradient wind was 15 knots or less, there was little fluctuation in the direction of the katabatic wind. However, when the gradient wind was 20 knots or more, there were more frequent fluctuations in the surface wind direction, with associated temperature changes.

At the times of such fluctuations, the surface wind was temporarily established from its normal direction, i.e. backed from the gradient wind and the loss of the cold katabatic airflow resulted in a rapid rise of air temperature. An example of this can be seen in Figure 2 at 1000–1100 GMT where the interruption of the katabatic flow is linked with a very sharp rise in temperature.

The interruption of the katabatic flow is thought to be due to the complex flow which must exist as a result of katabatic effects on all slopes. At times the combined katabatic forces at a location are likely to balance out and permit a break-through of the normal surface wind at a point which was previously affected by a katabatic wind. This effect has been fully studied at a different location in an earlier paper.[1]

Onset of katabatic flow.—The onset times of the katabatic flow were estimated to the nearest half hour and the conditions at these times noted. On 7 out of the 10 occasions, a non-fluctuating flow was observed, whereas, on the other 3, the katabatic flow was disturbed at first for 2–4 hours before becoming steady. Onset times varied from 1730 to 0200 GMT.

On each occasion of similar gradient wind speed, the steady katabatic flow (whether or not preceded by a fluctuating period) commenced at a very similar temperature. These temperatures can be seen plotted on Figure 3. The temperature at which the katabatic fluctuations commenced was also plotted in relation to its gradient wind speed. It is to be noted that no fluctuation took place at the time of onset when the gradient wind speed was less than 20 knots.

Cessation of katabatic flow.—The katabatic flow ceased between 0730 and 1330 GMT at temperatures ranging from −8.6°C to +1.8°C. There was however no apparent correlation between cessation temperatures and gradient wind speeds. It was noted that the greatest temperature rises were associated with the periods of greatest fluctuation.

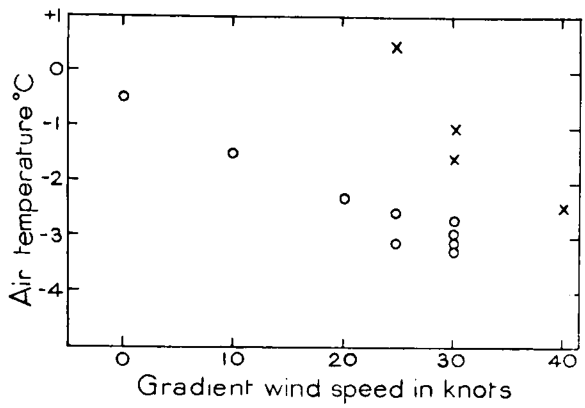

FIGURE 3—AIR TEMPERATURE AND THE ONSET OF THE KATABATIC FLOW

o Steady flow onset x Fluctuating flow onset

The gradient wind direction was 180–210°

Conclusions.—During a 10-day period of cloudless conditions, complete snow cover and large diurnal air temperature ranges, a katabatic wind, or a wind influenced by katabatic effects was recorded at Acklington every night. The speed of these winds was always in the range 5–10 knots.

At times, the katabatic flow was subject to fluctuations which were always reflected in the temperature curves. It is suggested that the fluctuations which only became frequent when gradient wind speed exceeded 20 knots are due to the complex katabatic flow which must take place in hilly regions.

REFERENCE

1. MCGINNIGLE, J. B.; Correlated fluctuations of wind direction and air temperature at Renfrew Airport on 12 October 1960. *Met. Mag., London,* **90,** 1961, p. 146.

REVIEWS

Nordlichtbeobachtungen in Ungarn (1523–1960), by A. Réthly and Z. Berkes, 7in. × 9½in., pp. 189, *illus.*, Akadémiai Kiadó, Budapest V, Alkotámny Utca 21. 1963. Price: $6.00.

The important task of searching the archives for records of aurorae in low latitudes in past centuries is not only arduous but presents formidable difficulties. Displays are so infrequent that observers are unfamiliar with the appearance and behaviour of the phenomenon. The low latitude aurora appears normally as a red glow on the poleward horizon, which may be quite unspectacular and so pass unrecorded unless it is exceptionally brilliant. Even in that case, it has often been mistaken for the reflection in the sky of a great fire and, indeed, it was responsible for unnecessary journeys northwards by fire engines in south-east Europe on several occasions as recently as the International Geophysical Year. Besides, descriptions of other phenomena, notably meteor occurrences, St. Elmo's Fire, crepuscular rays and unusually colourful sunsets may be confused with aurora. Sketches and paintings by observers provide the best evidence and some quite magnificent examples of these from the seventeenth and eighteenth centuries are reproduced in colour in this volume. The authors state that they have carefully checked the observations to eliminate cases of confusion with other phenomena; the earlier Hungarian observations were examined along with those in the well known catalogue of Fritz (1873) and the later data with records of sunspots and geomagnetic disturbance. The result of their labours is an impressive catalogue of displays observed in Hungary during 224 nights between 1523 and 1960.

The second part (34 pages) of the book presents a statistical analysis of the data. Annual, monthly and daily variations and variations of auroral frequency with latitude, sunspot number, geomagnetic disturbance and temperature are determined. A well marked parallelism is demonstrated between curves showing the secular variations of auroral frequency, sunspot number and mean temperature in middle Europe. The significance of some of the results of this analysis of inhomogeneous data, consisting sometimes of as few as 117 observations over a period of several centuries, is questionable.

This attractive book is sure to be widely consulted by those interested in auroral morphology.

J. PATON

Meteorobiologie und Elektrizität der Atmosphäre, by R. Reiter. 9¼in. × 6½in., pp.xii + 424, *illus.*,Akademische Verlagsgesellschaft, Geest & Portig K.-G., Leipzig, 1960. Price: D.M. 48.

This being a book of encyclopaedic scope and Teutonic thoroughness, any attempt at a full review would degenerate into a mere catalogue, and an incomplete one at that. However much of the book deals with the influence of weather on the onset of disease, and it soon becomes evident that the author's favourite meteorological factor is 'Infralangwellen'—infra-long waves—by which he means the radio waves emanating from electric discharges in thundery weather. But, since thunderstorms arise in an unstable atmosphere, there often seems to be some doubt whether the infra-long waves or other phenomena which accompany instability are the predominating factor.

The author's own work in this field appears to have started soon after the second world war. So the first medical condition he deals with is the pain from amputation stumps, including the 'phantom limb' sensation due to impulses caused to travel along nerves which formerly transmitted sensations from the missing limb to the spinal cord. In this case he finds that the intensity of pain is correlated with disturbances of the electrical field but not at all with the intensity of the infra-long waves; i.e. it is changes in the intensity of the latter that matter. Pain from brain injuries, on the other hand, is correlated with the intensity of the infra-long waves, but not with changes in their intensity.

Haemorrhages from the lung in tuberculous patients are 'weakly weather-conditioned,' but nevertheless there is a greater-than-random increase with 'unstable atmospheric layering, increased turbulence and cyclonic character,' —all of which are accompanied by increased production of infra-long waves— and also with Alpine föhn winds which penetrate to ground level. The onset of poliomyelitis, according to figures the author gives, is more probable in moist warm than in cold dry weather in the proportion of 119 : 91.

The section on disease ends with a discussion (pp. 170–173) on how all these results could be put to practical use in medical treatment, but amid much verbiage little emerges beyond a suggestion that observation of the weather might enable doctors in sanatoriums to plan ahead for an abnormal influx of patients.

A section on the influence of the weather on the timing of births is of particular interest to the reviewer, who once had to attend these functions over the whole of Lambeth, from Blackfriars Bridge to Kennington Oval, with only one fellow-student to share the work, just as the returned soldiers from the first world war were starting up their families again. It soon became obvious that these events tended to come in bursts, a couple of days' and nights' furious cycling around in an attempt to cope, interspersed with two or three days of well earned (comparative) rest. There was a strong presumption that the weather had something to do with it, and we might have written a useful thesis if we had been, at that time, familiar with stability and instability as meteorological terms. Dr. Reiter, anyway, has found a definite correlation. In Bavaria, during disturbed weather, the number of births per unit time was found to be 6 per cent higher in 'disturbed' than in 'undisturbed' weather. If an area 60–70 km in radius, centred on the weather observation point, was alone considered, the amplitude of the variation rose to 11.5 per cent. Unstable and cyclonic weather, turbulence, inbreak of moist warm air in summer, showers and thunderstorms, and even days of increased infra-long waves without cumulonimbus, were all accompanied by temporary increases in the birth rate. He gives figures of 2.3 per cent increase on the day after a cold front and 5 per cent increase when infra-long waves were at a maximum. The onset of deaths, the author says, is also more frequent at times of maximum infra-long waves, and vice versa.

There is much else of interest in the book, including the influence of weather on plants and animals and on accident proneness, the effects of solar eruptions, the therapeutic value of 'electro-aerosols,' etc. But its appearance at the onset of the Space Age poses a new problem, hitherto hardly foreseen: if minor fluctuations in our earth's environment are so disturbing to its human occupants how will they fare when they found colonies in the vastly different environments of other planets?

A. E. SLATER

Climatologie méthodes et pratiques, by H. Grisollet, B. Guilmet, and R. Arléry. 9½in. × 6¼in., pp. ix + 401, *illus.* Gauthier-Villars & Cie Editeur, Quais de Grands-Augustins, 55, Paris VI[e], France, 1962. Price: 50 NF.

This is a companion volume to Mesures en Météorologie,[1] both books forming part of a collection called Monographies de Météorologie published under the general editorship of A. Viaut, Director of the Météorologie Nationale.

It is an extremely well planned work, the subject unfolding itself with orderly precision as an attempt is made to deal with all its aspects. This admirable method has its dangers; it may cause undue emphasis on certain matters merely because they are part of the general scheme, which itself is so wide that to cover everything means stretching rather thinly here and there. But this is a danger of which the authors are well aware and they point out on the first page that the book is a guide rather than a treatise on climatology. It seems to me to occupy a good and useful average position.

It is certainly a good guide in the way it takes one in an articulate manner through the subject divided into three main parts. First, the basic notions of climatology: definition, agents, elements and dimensions of climates, observations and data and their treatment.

The second part, which the authors think is the most important, and which should certainly prove the most useful to the general meteorologist, deals with statistical methods. Conscious of the limitations already outlined, the authors steer a safe course between the rigorous treatment expected by specialist statisticians and the attitude of those experienced forecasters "....so conscious of the nature of continuous evolution of atmospheric phenomena and consequently inclined to study them from a determinist standpoint, that they might deem excessive the importance here given to the statistical approach." Here again the argument proceeds with such orderly sequence that it can be boarded at any stage by the non-specialist without strain. Classification and tabulation are followed by graphical representation and distributions; then the principal parameters for averaging, dispersal and shape, followed by the main forms of distribution, sampling, fit, and normals; then contingence and correlation, time series, periodicity, persistence and so on. This part ends up with a useful chapter on graphical representation of climatological data.

This exposition makes a very interesting contrast with our *Handbook of statistical methods in meteorology*,[2] that erudite pot-pourri which, a little awe inspiring at first—at any rate for the likes of me—gains on long browsing acquaintance, rather like a private collector's over-congested room. In the same vein, I might compare this book to a well indexed small public museum.

The third part, on applied climatology, is at once the most straightforward and the most controversial. The subject is first treated, very rapidly, from the meteorological aspect or contribution of climatology to the study of the causes of weather phenomena. There, confronted with a vast and difficult subject, the book is most like a guide. I would have liked to read some more about dynamic climatology, especially after the promising remarks on this subject in the introduction. Next the geographical aspect of climatology is given a fairly comprehensive and classical treatment, dealing with descriptive climatology and the various ways in which climates are currently classified. Finally, there is a chapter on "Aspect pratique de la climatologie appliquée," which I might translate as doubly applied climatology. This ranges, very rapidly perforce, over bioclimatology, including the human aspect, agroclimatology, hydrology, aviation meteorology, and various other practical applications, ending up with insurance risks assessments. Here a little more about developing operational research methods, especially from the United States, would have been in keeping with the generally well informed character of the book. But it must be remembered that development in this field is so rapid that, for instance, the important *Journal of Applied Meteorology* of the American Meteorological Society was not started in time (March 1962) to be included in the comprehensive list of books and periodicals given at the end of the book, where an index would also be very welcome.

I was surprised to see in Chapter VII that observations from aircraft were given as typical example of observations "non utilisable en climatologie."

Throughout the book expressions in English, German and Russian most commonly associated with certain concepts are used giving it a truly international character.

If he can cope with the language, it would be difficult to think of a more useful book for the applied meteorological analyst intrigued by the reiteration of certain features on the charts which confront him daily, or in the weather in which he finds himself immersed when he has time to lift his head or even stroll outside. This excellent guide should have a place on his library shelf.

REFERENCES

1. PERLAT, A. and PETIT, M.; Mesures en Météorologie. Paris, Gauthier-Villers, 1961.
2. BROOKS, C.E.P. and CARRUTHERS, N.; Handbook of statistical methods in meteorology. London, HMSO, 1953.

J. COCHMÉ

NOTES AND NEWS

The Royal Meteorological Society's visit to Bracknell

A party of 30 Fellows of the Royal Meteorological Society visited Bracknell on Wednesday 12 June 1963 for the Society's 'Summer Visit'. The party saw the communications centre and the forecast office before being given talks by Mr. Coles and Mr. Bushby on the techniques of forecasting. On the fifth floor they watched the electronic computer rapidly produce a forecast for the 500 mb level, and then fill in what was left of the 10-minute programme time allotted with a spirited rendering of 'The Volga Boatmen'. After visiting laboratories in the High Atmosphere and Instrument Branches, the members of the party were taken to the Experimental Site where they had tea. Finally, they watched a radiosonde ascent, followed the telemetry reception and the radar tracking, and saw the sferics network in action.

R. FRITH

Meteorological Magazine: increase in price

We regret that owing to further increases in the cost of printing and publication it has become necessary to raise the price of the *Meteorological Magazine*. The price will be 3*s*. 0*d*. an issue with effect from the January 1964 number. The net annual subscription will become 39*s*. including postage. Present subscribers will remain on the existing rate until renewal of their subscriptions is due.

PUBLICATION RECEIVED

The Weather: Precipitation (in the series "Geography–meteorology"). 30 in. × 40 in., Wallchart (C 887) in two colours, Educational Productions Ltd., East Ardsley, Wakefield, Yorkshire, 1963. Price 10*s*.

LETTERS TO THE EDITOR

The sub-sun

May I make a few observations on the very interesting photograph of the sub-sun in *Meteorological Magazine*, Volume 92, page 254.

The brilliance of the reflection might lead one to suppose that, unless of course there was no cloud available, it would generate parhelia. Also there is another point. These may not have shown on the photograph, but it appears that, according to Visser (*Handbuch der Geophysik*, 8, 1961, p. 1038) that due to total reflection on the lower side of the plates, interference may occur giving rings round the image, (Figure 358, p. 1039 in the above volume and *Met. Z. Braunschweig*,55, 1938, p. 265). Also (p. 1035 in *Handbuch der Geophysik*) the sub-sun may, in the polar regions with a low sun, be seen from the ground. It was observed frequently at Maudheim; on August 17 1951, from the meteorological mast, it could be seen on the level snow.

Incidentally, in his recent entertaining work on the flying saucer mania, Dr. D. H. Menzel (*The world of flying saucers* by Menzel and Boyd Doubleday, New York, 1963) thinks the sub-sun is the source of many reports. He tells me privately it and its parhelia can, from a fast plane, perform amazing antics and deceive the unwary.

Rockmount Hotel, Tunbridge Wells, Kent. CICELY M. BOTLEY

Reply from Mr. G. J. Jefferson:

The sub-sun was visible for about 15–20 minutes (which in a Boeing 707 means 120–150 nautical miles), the photograph being taken towards the end of this period when, as can be seen in the photograph, the cirrus was beginning to thin out. During the period of observation I did not see any parhelia generated by the sub-sun. I do not think there were any, though I cannot be absolutely certain about this since the angle of vision may possibly not have been wide enough to observe them. The aircraft windows were about 12 inches wide and glazed with three layers of perspex separated by gaps of an inch or so. On one side parhelia could have been hidden by the wing of the aircraft. There was no sign of any coloured bands or fringing round the sub-sun which was quite white.

Meteorological Office, London (Heathrow) Airport.

Funnel cloud observations at Bracknell

The following is an account of observations taken between 1225 and 1300 GMT from the Meteorological Office roof, Bracknell, on Monday, 2 September 1963:

1225 GMT: A large intense black cloud covered approximately half the sky, from SE to NW, through SW, and up to the zenith. Precipitation was seen falling heavily in the distance, from the more central parts of the cloud. The rest of the sky was covered with much smaller and less significant clouds, with small patches of blue sky between them. Between 1225 and 1300, the main cloud slowly but steadily approached, and also shifted somewhat to the right, but small patches of blue sky continued to be visible in the NE part of the sky. The area of heavy precipitation also shifted with the general movement of the cloud, and the nearest part of it was within a mile or two of the Meteorological Office between 1245 and 1300, during which time the main cloud covered most of the sky, including all the sky overhead. Continuous but slight rain fell at the Office between 1245 and 1300. A funnel cloud was seen in the NW at 1225, reaching about half way down to the ground, from the extreme right-hand part of the base of the main cloud, which in that vicinity was only shallow, and not very dark, the cloud base being about 10° in elevation there. During the next 10 minutes, the funnel cloud fluctuated somewhat in length and thickness, but did not alter materially until 1235, when it shrank fairly quickly to about half its original length, and then continued with little change until 1300. It also retained the same azimuth and elevation, so far as I could tell.

1235 GMT: Activity began to take place in the WSW, with a chaotic turmoil in some ragged clouds just below the main base level of the cloud, at an elevation of about 30°, and this effect was more or less continuous until 1300, though by that time, the centre of turmoil was in the W, at an elevation of about 45°. When this swirling turmoil had been underway for a minute or two, an object like a plume of smoke was seen rising quite quickly (while also fluctuating in intensity) from a point on the ground about a mile away. This happened simultaneously with the appearance, between it and the swirling cloud-base, of ragged shreds of cloud, which seemed to change shape and vertical position very rapidly, besides disappearing and reappearing with equal rapidity. But after perhaps another minute, there was a complete link-up from cloud to ground, which only lasted for a fraction of a minute, but long enough to see that the tornado vortex was moving slowly but visibly towards the right. Immediately afterwards, the vortex (which had been only pencil-thin at the ground) dissolved rapidly, and by 1240 it had completely vanished, leaving only the turbulent swirling motion in the base of the cloud, from which I saw the funnel cloud extend a short way downwards from the base of the cloud once or twice between 1240 and 1300. However, I was told that at 1250 the vortex had extended to the ground again for a short time, though I did not see this myself as I was away fetching a raincoat for those few minutes. The tornado that I saw briefly at about 1238 was in front and somewhat to the right of the heaviest precipitation, while the funnel cloud in the NW must have been well clear of any precipitation. There were a few not very loud rumbles of thunder between 1240 and some time after 1300.

Meteorological Office, Bracknell E.C.W.GOLDIE

[See Plate IV opposite page 365 for photographs of the funnel cloud. Ed. M.M.]