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RUNWAY LIGHT RANGE AS A SUBJECTIVE MEASUREMENT

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Summary.—Data obtained from personal calibration with a Gold visibility meter are used to assess the variation in visual acuity of the human eye. A formula is developed relating the difference in reports of runway light range to the variation in visual acuity.

Introduction.—Pilots of aircraft landing at civil State airfields in the United Kingdom in foggy conditions are supplied with a report of the runway light range shortly before landing. The runway light range is the distance along the runway to which the runway lights can be seen from a point fifteen feet above the centre line of the runway and near the touch-down point. It is assessed by an observer on the ground on the basis of the number of lights he can see along the runway and it is usually significantly greater than the meteorological visibility along the same path. Owing to the variation in visual acuity both for one observer at different times and for different observers the estimation of runway light range is a subjective matter and it has seemed worth-while attempting to assess the extent to which this may be responsible for differences in the estimates by the observer and the pilot.

There are practical difficulties in getting simultaneous assessments of runway light range by two different observers. There are available, however, the results of a number of personal calibrations by observers using the Gold visibility meter. In performing such a calibration the observer measures the opacity of the optical screen which will just obscure a fixed light at a fixed distance. This opacity is a measure of the visual acuity of the observer at that instant. The available data include successive calibrations by the same observer and also calibrations by different observers using the same light. From these data it is possible to infer something about the variation of visual acuity with time and with observer.

The available data are not in a form convenient for direct assessment of the differences between pairs of observers. We may consider the visual acuity of an observer as made up of three parts. The main part is the average visual acuity of all observers at all times. There is a second part which varies from one observer to another but is constant with time. There is a third part which varies with time for any one observer but the range of variation of which is probably similar

for all observers. With these concepts we shall deduce the probable difference between a pair of observers. Before doing this it is convenient to recapitulate some general relationships and then to examine the standard procedure when using a Gold visibility meter.

Some general relationships.—The relationship between the candle-power C of a light, the distance d (yards) at which it is just visible to a human eye and the opacity N (nebules) of the optical screen between the light and the eye is given by

$$\log C - 2 \log d = 0.03N + k, \qquad \dots \dots (1)$$

where the logarithms are to base 10 and k depends upon the acuity of the human eye. For a standard observer who can just detect 0.15 kilometre-candles the value of k is -6.9 . Variation from one observer to another is reflected in different values for k . If two observers characterized by k_1 and k_2 can just detect the same light at the same distance when the intervening optical screen has values N_1 and N_2 nebules respectively then

$$k_1 - k_2 = 0.03 (N_2 - N_1). \qquad \dots \dots (2)$$

If the optical screening is solely the result of atmospheric opacity it may be convenient to write

$$N = dn, \qquad \dots \dots (3)$$

where n is the number of nebules per yard.

Consider two observers noting the distance to which a light can be seen. If they obtain estimates d_1 and d_2 ($d_1 > d_2$) then from Equations (1) and (3) we get

$$2 \log (d_1/d_2) + 0.03n (d_1 - d_2) + k_1 - k_2 = 0.$$

Writing $\Delta = (d_1 - d_2)/d_2$, expanding the logarithm and retaining only two terms in the expansion on the assumption that Δ is small we get

$$0.434 \Delta^2 - (0.868 + 0.03n d_2) \Delta + k_2 - k_1 = 0.$$

Since Δ is small (we shall see later it is of the order of 0.1) we can, to a first approximation, neglect the quadratic term and write

$$\Delta = \frac{d_1 - d_2}{d_2} = \frac{0.03(N_1 - N_2)}{0.868 + 0.03 N_2}. \qquad \dots \dots (4)$$

There is one further equation which we shall find useful. Assuming a threshold contrast of 0.02 for perception by the human eye we can write

$$N V = 56 d, \qquad \dots \dots (5)$$

where N is the opacity (nebules) of an atmospheric screen of thickness d (yards) and V is the meteorological visibility (yards).

It is convenient here to write a statistical relationship in terms of the concepts outlined at the end of the Introduction. Suppose

$$N = K + a + b,$$

where K = a mean value for all observers and all occasions with the same light and distance,

$K + a$ = a mean value for one observer but a varies from one observer to another,

b varies from occasion to occasion with any one observer but the frequency distribution of values is the same for all observers.

Then if N_i and N_r are two assessments by different observers

$$N_i - N_r = (a_i - a_r) + (b_i - b_r)$$

$$\text{and } (N_i - N_r)^2 = 2A^2 + 2B^2, \quad (6)$$

where A and B are root mean square values of a and b respectively.

The Gold visibility meter.—The Gold visibility meter is used in conjunction with lights of supposedly fixed candle-power installed at fixed distances. The recommended lamps and distances are 10 watts at 100 yards, 100 watts at 500 yards and 100 watts (or higher if possible) at 1,500 yards. It is a standing instruction that each observer shall carry out a “personal calibration” on each light as often as circumstances permit. The object of the calibration is to determine the opacity (in nebules) of the optical screen necessary to obscure the light from the observer. To perform the calibration the observer selects a night when the visibility is good and in any case not less than twelve times the distance of the light. This visibility is estimated. The atmospheric opacity between the observing position and the fixed visibility light is then (from Equation (5)) $56d/V$ and so is less than five nebules. It seems unlikely that the error in estimating this atmospheric screen will often exceed one nebule. The observer interposes an optical wedge between his eye and the light and adjusts it to a value of N_1 nebules at which the light is only just visible. The total opacity between his eye and the light is now $N_1 + 56d/V$. This is his personal calibration figure, N_0 , for that light.

In routine use of the Gold visibility meter the observer selects the farthest visibility light which he can see and adjusts the visibility meter to a value, say N_2 nebules, at which the light is just obscured. The opacity of the atmospheric screen is then $(N_0 - N_2)$ and the equivalent daylight visibility is $56d/(N_0 - N_2)$. This method of measuring visibility is not used if $(N_0 - N_2)$ is less than eleven nebules.

In order to reduce the effect of variable dark adaptation of the eye the observer is instructed to start his observation two minutes after leaving a well lighted room.

The personal variation shown by Gold visibility meter data.—From the records of “personal calibrations” with a Gold visibility meter at various outstations those figures have been abstracted which apply to observers who have carried out at least three calibrations on the same set of visibility lights. Generally the calibrations were carried out over a period of several months. If one can assume that the candle-power of the visibility lights remained constant the mean value of the calibrations obtained by one observer for one light would correspond to $(K + a)$ at the end of the section on “general relationships”, and the departures of the individual readings from this same mean value would correspond to b . The root mean square value of b corresponds to B of the same section. Table I gives the mean calibration figure for each observer with each light, the standard deviation, B , of his readings about his mean value and the number of observations contributing to each figure.

There are certain curious features about some parts of Table I. At London Airport each observer separately found a greater variation when using the lights at 100 and 512 yards than when using the other lights. It seemed possible that there were significant variations in the voltage applied to these nearer lights.

TABLE I—MEAN CALIBRATION FIGURES WITH THE GOLD VISIBILITY METER AND
THE STANDARD DEVIATION ABOUT THE MEAN

London Airport

Observer	Distance of visibility light in yards					Distance of visibility light in yards					Distance of visibility light in yards				
	100	512	852	1617	2458	100	512	852	1617	2458	100	512	852	1617	2458
	Mean value in nebules					Standard deviation in yards					Number of observations				
R	177.1	136.7	117.9	105.5	89.7	10.3	11.6	4.5	6.2	10.0	8	8	8	8	7
S	177.0	119.9	112.3	105.3	92.4	5.4	4.8	2.0	0.7	4.3	10	9	10	7	5
T	148.7	116.0	97.5	83.7		14.9	7.0	5.4	3.6	—	4	4	4	4	—
L	156.0	118.2	102.2	82.7	71.7	8.6	19.1	8.3	5.8	7.8	4	4	4	3	4
Mean			107.5	94.3	87.9										

Elmdon Airport,
Birmingham

Observer	Distance of visibility light in yards				Distance of visibility light in yards				Distance of visibility light in yards			
	100	500	600	1500	100	500	600	1500	100	500	600	1500
	Mean value in nebules				Standard deviation in yards				Number of observations			
D	104.3	107.3	113.0	103.3	0.5	0.5	3.6	2.6	3	3	3	3
A	106.7	103.7	108.0	101.0	4.0	6.7	1.4	3.7	3	3	3	3
T	110.3	106.0	106.3	92.7	2.1	3.6	5.9	6.8	3	3	3	3
P	98.7	102.7	95.3	96.7	2.6	4.1	3.3	4.6	3	3	3	3
H	103.3	110.3	109.7	98.7	5.4	5.3	11.6	16.3	3	3	3	3
Mean	104.7	106.0	105.7	98.4								

Rhoose Airport,
Cardiff

Observer	Distance of visibility light in yards			Distance of visibility light in yards			Distance of visibility light in yards		
	100	500	1350	100	500	1350	100	500	1350
	Mean value in nebules			Standard deviation in yards			Number of observations		
A	—	112.2	—	—	15.5	—	—	3	—
B	143.3	124.9	109.2	7.3	10.9	4.8	4	5	4
C	126.2	133.0	110.3	14.9	3.2	2.2	4	5	4
D	132.3	129.0	103.5	10.9	10.1	7.9	5	4	3
E	126.2	111.4	95.6	10.0	4.1	5.1	5	6	6
F	134.4	135.3	—	9.2	10.5	—	4	3	—
Mean	132.5	124.3	104.7						

Renfrew Airport,
Glasgow

Observer	Distance of visibility light in yards			Distance of visibility light in yards			Distance of visibility light in yards		
	110	720	1270	110	720	1270	110	720	1270
	Mean value in nebules			Standard deviation in yards			Number of observations		
W	112.0	90.1	75.9	3.5	4.4	1.9	4	4	4
F	141.1	114.2	103.3	1.7	3.3	2.0	4	4	4
C	141.6	117.2	100.0	2.3	6.7	2.5	5	5	5
X	95.7	84.5	78.4	2.0	1.5	0.5	4	4	4
Mean	131.6	107.2	93.1						

Speke Airport,
Liverpool

Observer	Distance of visibility light in yards			Distance of visibility light in yards			Distance of visibility light in yards		
	150	555	1050	150	555	1050	150	555	1050
	Mean value in nebules			Standard deviation in yards			Number of observations		
B	110.1	—	89.8	4.5	—	2.2	5	—	5
X	115.5	113.1	96.5	4.0	1.3	7.7	6	3	6
M	118.2	104.0	99.8	4.0	1.8	1.5	4	4	5
Mean	114.6	108.5	95.7						

The identification letters for the observers follow a self-contained system for each station so that, for example, A at Elmdon Airport is not to be identified with A at Rhoose Airport.

Observer H at Elmdon Airport (Birmingham) found abnormally large variations at 600 and 1,500 yards. Reference to the raw data showed that H made his three calibrations over a period of one month and, at these two distances, showed a large and steady improvement. This may have resulted from changes in the lights. The mean values obtained by X at Renfrew Airport (Glasgow) are abnormally low, though the standard deviations conform to the pattern. Enquiry revealed that this observer is "long-sighted". In what follows all London Airport figures obtained at 100 and 512 yards, figures obtained by H at 600 and 1,500 yards at Elmdon and all values by X at Renfrew have been excluded.

After excluding these doubtful values there remain 272 personal calibration figures. If these are grouped by station and the variations still determined by noting the difference between the observation and the mean value appropriate to the particular observer and light, the standard deviations, *B*, are as shown in Table II. The differences between the stations may be the result only of differences in the observers or they may be influenced by variations in the power of the visibility lights.

TABLE II—FREQUENCY DISTRIBUTION OF VARIATION OF NUMBER OF OBSERVED VARIATIONS EXCEEDING pB OR pA

				Value of p				Number of observations
				0.5	1.0	1.5	2.0	
				<i>percentage</i>				
Normal error law	...	...	...	61.8	31.8	13.4	4.5	100
		B		Variations from personal mean exceeding pB				
				<i>number</i>				
L.A.P.	...	...	5.73	39	19	7	3	64
Elmdon	...	...	4.14	28	15	4	2	54
Rhooe	...	...	8.95	43	22	9	4	65
Renfrew	...	...	3.20	31	11	6	3	51
Speke	...	...	4.04	21	8	3	2	38
Total	...	...		162	75	29	14	272
				<i>percentage</i>				
Total	...	...		59.5	27.6	10.7	5.1	
				<i>number</i>				
All stations	...	...	5.87	145	70	36	14	272
				<i>percentage</i>				
Total	...	...		53.4	25.7	13.2	5.1	
		A		Variations of personal mean exceeding pA				
				<i>number</i>				
L.A.P.	...	...	9.72	8	7	1	—	11
Elmdon	...	...	4.37	11	6	2	1	18
Rhooe	...	...	7.60	11	6	2	—	15
Renfrew	...	...	12.75	9	3	1	—	9
Speke	...	...	3.79	3	2	1	—	6
Total	...	...		42	24	7	1	59
				<i>percentage</i>				
Total	...	...		71.2	40.6	11.9	1.7	
				<i>number</i>				
All stations	...	...	8.02	40	21	5	4	59
				<i>percentage</i>				
Total	...	...		67.8	35.6	8.5	6.8	

It is useful to examine these variations from the personal mean a little more closely in order to determine the frequency of large variations. There are various ways in which this can be done but the following procedure was adopted. The data were grouped by station. In each group the variations from the personal means were compared with the station value for the standard deviation (tabulated in Table II) and the number of variations exceeding pB , where B is the station value of the standard deviation and p has the values 0.5, 1.0, 1.5 and 2.0 in turn. An alternative to this procedure is to group all stations together and to compare the variations with the over-all standard deviation of 5.87 nebules. The results of both procedures are shown in the upper half of Table II with, for comparison, similar figures obtained from the normal error law. The two procedures give rather similar results and, in view of the small number of observations, the similarity to the corresponding figures obtained from the normal error law is quite close.

The variation between observers shown by Gold visibility meter data.—The mean values of the calibration figures in Table I provide data for assessing the variation from one observer to another. The data are not fully adequate for various reasons. The number of calibrations per observer is too small to give reliable mean values. The number of observers using each light is too small and the period in which the observations were made varies from one observer to another.

After excluding the doubtful observations already discussed the average of the mean calibration figures, K , for all observers using any one light was formed and the variations of the mean personal calibration figures from the average (a) were computed. These variations were then treated in the same ways as the variations from the personal mean as described above. The results are given in the lower half of Table II. The two alternative procedures produce results which are similar and approximate reasonably closely to the normal error law.

The validity of Equation (1).—Before continuing with consideration of the variations which occur it is interesting to examine how far the data support the validity of Equation (1). Table I gives the mean values for all observers and all occasions (excluding the doubtful cases already discussed) of the screens required to obscure each light at each station. The wattage of the lights was determined and converted to candle-power on the basis of data obtained from *The Electrical Year Book* as follows

Wattage	...	...	15	60	100
Candle-power	...	...	8.01	41.7	83.2

In Figure I the mean values in Table I have been used to plot $(0.03N - \log C)$ against $\log d$. The line in that figure was constructed to have a slope of -2 . In view of the nature of the data used it is considered that the line is a very

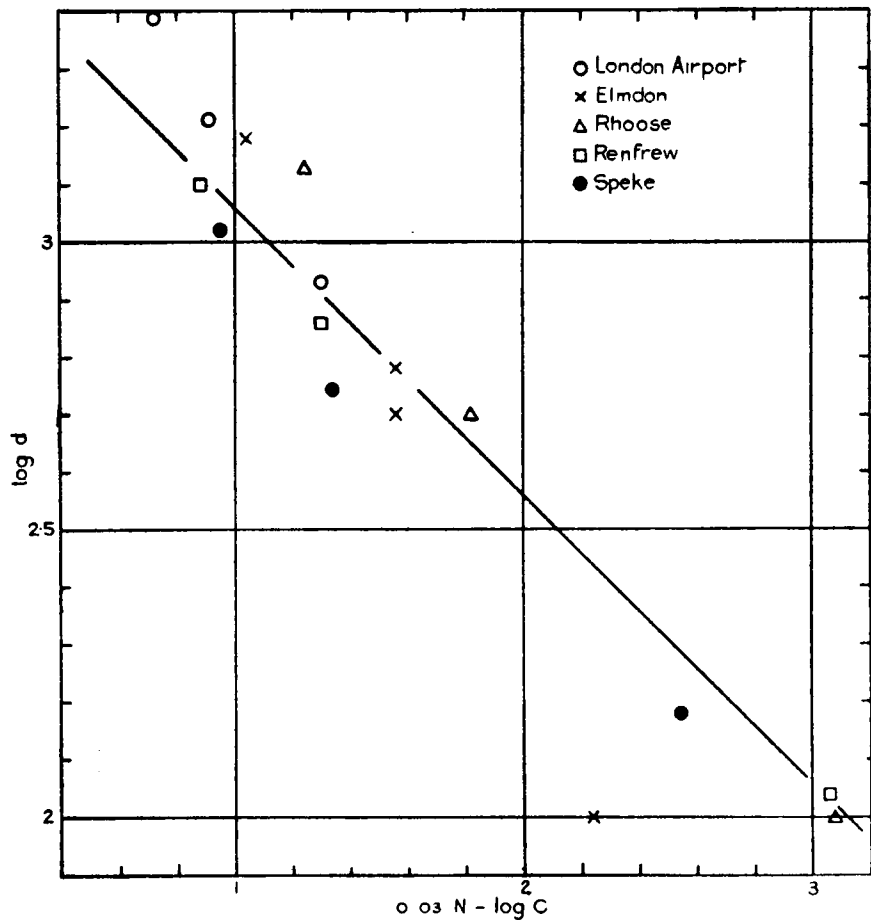


FIGURE I

satisfactory fit except for the Elmdon point at 100 yards. The value of k corresponding to the line is -7.12 implying an ability to detect 0.091 kilometre-candles.

The difference between simultaneous observations by two observers.—With the concepts embodied in Equation (6) we have seen that the frequency distributions of both a and b follow a normal error law and, of course, the mean values of a and b are both zero. Table II shows that the standard deviations are about 8 nebules for a and 6 nebules for b . Bearing in mind the variation in a and in b from station to station as shown in Table II it is difficult to be sure that there is any real difference between the over-all values of a and b . It is certainly convenient for computational purposes if a and b are the same and we shall accordingly assume that both a and b have normal frequency distributions, with mean values zero and each with a standard deviation of 7 nebules. With these assumptions it is permissible to assume that $(N_i - N_j)$ has a normal frequency distribution, with a mean value zero and a standard deviation of 14 nebules $(= \sqrt{(2 \times 49 + 2 \times 49)})$. From Equation (4) we see that

$$d_1 - d_2 = d_2 \frac{0.03(N_1 - N_2)}{0.868 \times 0.03 N_2} \quad \dots \dots \dots (7)$$

Now the lights used by the observer in assessing the runway light range are likely to lie within the power range 100 to 500 candle-power and the distances of interest to aviation are from 400 to 1000 yards. Over these ranges we can use Equation (1), with $k = -7.1$ from Figure 1, to show that $0.03N$ varies from 3.1 to 4.6. We can then take the denominator of the right-hand side of Equation (7) to be 4.8 as a fairly close approximation and hence

$$d_1 - d_2 = \frac{d_2}{160} (N_1 - N_2) \quad \dots \dots \dots (8)$$

For convenience we shall now change the notation and, putting $d_1 - d_2 = x$, $N_1 - N_2 = y$ and $d_2/160 = f$, we get

$$x = fy, \quad \dots \dots \dots (9)$$

where f depends upon the value of d_2 and y has a normal frequency distribution with a standard deviation of 14 nebules. For a fixed value of d_2 it follows that x has a normal frequency distribution with a standard deviation $\sigma = 14f$.

We have so far assumed that the distance of the light from the observer is a continuous function. In practice this is not true. The observer assesses the runway light range on the basis of the number of lights visible to him, the lights being separated by finite intervals. Clearly it might happen that two observers would report the same runway light range not because they had the same visual acuity but because one could just see (say) nine observation lights and the other only just failed to see ten lights. We must therefore examine the effect of the finite spacing of observation lights on the difference in reported values of runway light range by two observers.

Suppose the observation lights are spaced at intervals of c yards and consider the case when $mc < x < (m+1)c$. The observer, D_1 , with the greater visual acuity will see at least m lights further than D_2 and he may see $(m+1)$ lights further. Which of the two conditions obtains depends upon how far into the furthest interval, c , the visual range of D_2 penetrates. We can divide the

interval, c , in which D_2 's visual range ends into two parts, namely, a near part $(c + mc - x)$ and a further part $(x - mc)$. If D_2 's visual range falls within the near part D_1 's visual range will fall short of $d_2 + (m + 1)c$ and the reported difference will be m lights. We must consider that all points in a particular interval c are equally likely for the limit of D_2 's range. It follows that when $mc < x < (m + 1)c$ the probability that the reported difference shall be m lights is $(c - x + mc)/c = (m + 1) - x/c$ and this fraction of the occurrences of x lying between mc and $(m + 1)c$ will lead to a reported difference of m lights.

Now the frequency of occurrence of x is

$$\frac{2}{\sigma} \frac{1}{\sqrt{2\pi}} \exp (-x^2/2\sigma^2) dx,$$

where σ is $14 f$ and the initial factor 2 arises from the fact that negative and positive values of x are included. It follows that

$$F(m) = \frac{2}{\sigma\sqrt{2\pi}} \left[\int_0^{mc} e^{-x^2/2\sigma^2} dx + \int_{mc}^{m+1} c \left(m + 1 - \frac{x}{c} \right) e^{-x^2/2\sigma^2} dx \right],$$

where $F(m)$ = fraction of observations in which the reported difference in runway light range does not exceed mc .

For computational purposes this expression is easily reduced to

$$F(m) = 2 \left[(m + 1) R(m + 1) - m R(m) \right] + \frac{2}{p\sqrt{2\pi}} \left[S(m + 1) - S(m) \right], \tag{10}$$

where

$$R(m) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^{mp\sigma} e^{-x^2/2\sigma^2} dx,$$

$$S(m) = \exp (-m^2p^2/2),$$

$$c = pa.$$

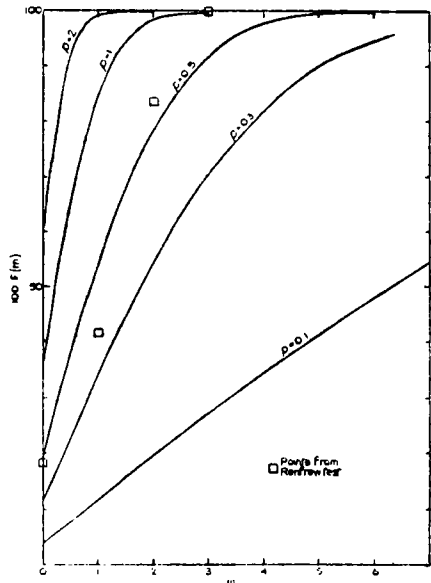


FIGURE 2

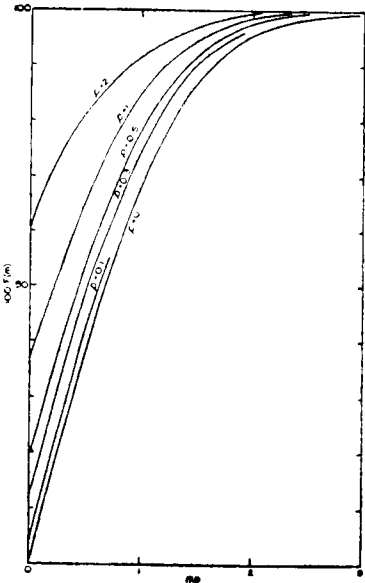


FIGURE 3

In this form $F(m)$ is easily evaluated from standard tables for specified values of m and p . This has been done and the results are plotted in two ways in Figures 2 and 3. In Figure 2, $F(m)$ is plotted against m for various values of p . Each curve shows the percentage number ($F(m)$ has been multiplied by 100) of observations in which the reported differences in runway light range will not exceed m lights. The different curves correspond to different spacings of the observation lights.

Although assessments of runway light range are based upon the number of lights seen by the observer the report is given in terms of distances. This is the relevant variable for the pilot. A difference of m lights in assessment of runway light range corresponds to a difference of $m c = m p \sigma$ yards. Accordingly in Figure 3, $100 F(m)$ has been plotted against $m p$. These curves give the percentage number of observations for which the difference between two assessments of runway light range will not exceed $m p \sigma$ yards. They illustrate that as the spacing of the observation lights decreases the agreement between two observers deteriorates. Consider for example occasions when D_2 has a visual range of 800 yards. Then $f = 800/160 = 5$ and $\sigma = 5 \times 14 = 70$ yards. From Figure 3 we can now extract the percentage number of occasions on which the differences exceed specified amounts as follows:

				light spacing in yards				
				0	21	35	70	140
					Percentage	number of occasions		
Differences exceeding 70 yards	...	...	32	24.5	21.5	15	8.5	
Differences exceeding 140 yards	...	...	4.6	2.2	2.2	1.3	0.7	

These curves and the values given above are, of course, based on a standard deviation of 14 nebules for $(N_2 - N_1)$. This figure was obtained from calibrations with a Gold visibility meter in the making of which staff are instructed to allow two minutes to elapse after leaving a lighted room before making an observation. It seems highly probable that if $(N_2 - N_1)$ refers to the difference between a ground-based observer looking at observation lights along a runway and a pilot in the cockpit of an aircraft which has just descended down the glide path through the approach lighting, then the standard deviation of $(N_2 - N_1)$ may be considerably greater than 14 nebules and the distances quoted in the above table would need to be increased accordingly.

A test at Renfrew.—On 2 December 1957 a few observations of the number of runway lights visible to four observers were made. The results were as follows:

					Time (G.M.T.)			
					1550	1605	1610	1612
					Number of lights visible			
Observer A	...	...	...	...	6	7	8	8
Observer B	...	...	...	...	8	9	11	11
Observer C	...	...	...	...	7	7	—	—
Observer D	...	...	...	...	—	—	10	9

In this test the sixth light was at a distance of 400 yards and the light spacing was 66 yards. These data are unsatisfactory for comparing with the formulae developed above both because there are too few data and because d_2 varies so much. However, since there seemed to be no other data available the frequency

distribution of differences (in terms of number of lights) of the twelve possible pairs shown above have been extracted as follows:

Number of lights difference	...	...	0	1	2	3
Percentage number of differences	...	...	8.3	41.7	83.3	100

These points have been plotted on Figure 2 and it will be seen that they fall fairly near the curve for $p = 0.5$. The spacing of the lights was 66 yards so this would imply a standard deviation of 132 yards for x . The mean value of d_2 (say midway between the 7th and 8th lights) was 500 yards so the preceding sections would indicate a standard deviation of only $(500/160) \times 14 = 44$ yards. The discrepancy is probably to be attributed to a wrong value for the standard deviation of $(N_2 - N_1)$. In the circumstances of these observations, variation in the state of dark adaptation of the eye was probably playing a large part and it may well have been also that 14 nebules is too small for the standard deviation of $(N_2 - N_1)$ even under controlled conditions. The result has been to (approximately) treble the value of $(N_2 - N_1)$.

Conclusions.—The frequency distribution of differences between two assessments of runway light range is given in terms of the standard deviation of visual acuity by the curves in Figure 3. The differences depend upon the spacing of the observation lights, being greater as the spacing diminishes. The standard deviation of visual acuity under partially controlled conditions is given approximately by $14 d/160$ (yards) where d is the smaller visual range. In practice and when no precautions to standardize visual acuity are possible the factor 14 may be increased two or three times.

NOTE ON A TABULATED FUNCTION FOR USE WITH TWO-DIMENSIONAL WIND DISTRIBUTIONS

By R. W. GLOYNE, B.Sc.

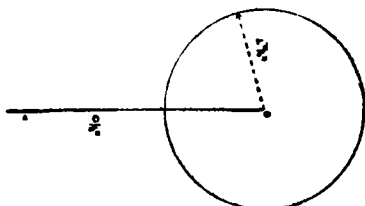
Knighting¹ has pointed out that the cumulative frequency of wind vectors for speeds from 0 to V summed over all directions is given by

$$F_V = \frac{2}{\sigma^2} \int_0^V \exp \left[-\frac{V^2 + V_R^2}{\sigma^2} \right] I_0 \left(\frac{2V V_R}{\sigma^2} \right) V. dV, \quad \dots \dots (1)$$

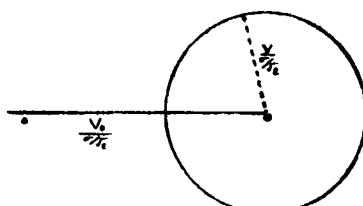
where σ is the *standard vector deviation*, V is the wind speed and V_R the vector mean speed.

Whilst working on wind distributions, a publication entitled *Offset circle probabilities*² (The Rand Corporation) came to my notice in which Equation (1) has been tabulated; a brief account of the contents might be of interest to meteorologists.

Let A be the centre of a normal circular distribution, O the origin of co-ordinates and $\sigma_x (= \sigma_y \equiv \sigma/\sqrt{2})$ the *linear standard deviation*.



(a) Notation used in tabulated function.²



(b) Notation customarily used in wind analyses.³

The tables in the publication are set out in terms of $(r_d - D)/\sigma_x = -3.9$ (0.1) 4.0 as abscissa and $D/\sigma_x = 0$ (0.1) 5.9 (0.5) 10.0 (1.0) 20.0 as ordinate, and give the probability (q) of a vector end falling outside the region bounded by the circle (O, r_d/σ_x).

Example (1): Let $V_R = 1$, $V = 4V_R$ and $V_R/\sigma = 1/2.05$.

$$\left[(r_d - D)/\sigma_x \equiv \right] \frac{\sqrt{2}V - \sqrt{2} V_R}{\sigma} = 3\sqrt{2} \frac{V_R}{\sigma} = 2.079,$$

$$\left[D/\sigma_x \equiv \right] \frac{\sqrt{2} V_R}{\sigma} = \frac{\sqrt{2}}{\sigma} = 0.690,$$

giving $q = 0.043$ or $p (= 1 - q) = 0.957$ (compared with 0.958 from *Geophysical Memoirs* No. 85, Table XXVIII³).

Example (2): $V_R = 8.8$ knots, $V = 21.1$ knots ($\equiv 2.4 V_R$) and V_S (mean scalar speed) = 22.0 knots. Hence $V_R/V_S = 40$ per cent corresponding to $\sigma/V_R = 2.64$ (*Geophysical Memoirs* No. 85, Table XXIX³).

$$\text{Thus } \left[(r_d - D)/\sigma_x \equiv \right] \frac{\sqrt{2}(V - V_R)}{\sigma} = \frac{\sqrt{2} \times 1.4}{2.64} = 0.750,$$

$$\left[D/\sigma_x \equiv \right] \frac{\sqrt{2} V_R}{\sigma} = \frac{\sqrt{2} \times 1}{2.64} = 0.536,$$

giving $q = 0.487$ hence $p = 0.513$ (compared with 0.514(6) from *Geophysical Memoirs* No. 85, Table XXIX³).

The "Rand" tables extend to cases corresponding to high values of V_R/V_S , and in general a double interpolation is required.

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TWENTY-FOUR HOUR FORECASTS BY THE METHOD OF ESTOQUE

By D. G. JAMES, Ph.D. and R. C. SMITH, Ph.D.

Introduction.—Estoque^{1,2} described a method of forecasting the heights of the 1000- and 500-millibar surfaces by graphical integration of the equations of motion for a model atmosphere similar to that of Sawyer and Bushby.³ At the level of non-divergence, assumed to be 500 millibars, the Estoque method is similar to that of Fjørtoft,⁴ barotropic forecasts being constructed by graphical integrations. To obtain forecasts at 1000 millibars additional assumptions are made which concern the baroclinicity of the lower layers of the troposphere.

A test of the method was carried out at the Forecasting Research Division at Dunstable, forecasts from 0300 G.M.T. data for 24-hour periods being made each weekday from 15 October 1956 to 9 November 1956. The trial period was chosen by the availability of staff rather than by synoptic considerations.

Some attempt is made to assess the accuracy of the forecasts by comparison with actual charts, and also to compare the graphical forecasts with those prepared on more conventional lines by the Central Forecasting Office, Dunstable. Estoque² considered that the best comparison could only be obtained by the visual examination of relevant charts. Consequently the accuracy of the forecasts was assessed by five experienced meteorologists; correlation coefficients were also evaluated for the Estoque and conventional forecasts for three fixed points on the chart.

Method. Symbols used.—

d	=	gridlength = 600 miles
f	=	Coriolis parameter = $2 \omega \sin \varphi$
ω	=	earth's angular velocity
φ	=	latitude
g	=	acceleration due to gravity
p	=	pressure
\mathbf{V}	=	horizontal velocity
w	=	vertical velocity
z	=	contour height
$z_0(x, y)$	=	height of 1000-millibar surface at the grid point (x, y)
$z_L(x, y)$	=	height of 500-millibar surface at (x, y)
\bar{z}_L	=	$\frac{1}{4} [z_L(x+d, y) + z_L(x-d, y) + z_L(x, y+d) + z_L(x, y-d)]$
B	\equiv	$\left(1 + \frac{0.56f^2 d^2}{m^2 g z_L \log \theta_L/\theta_0}\right)^{-1}$

where m is the magnification factor of the chart and θ the potential temperature.

$$G \equiv \int_0^\varphi \frac{d^2 f^2}{4g m^2} \cot \varphi d\varphi.$$

Basic assumptions.—The basic assumptions made are:

- (i) Quasi-geostrophic, adiabatic frictionless motion.
- (ii) Hydrostatic equilibrium.
- (iii) Vertical velocity zero at 1000 millibars, and varying sinusoidally to a numerical maximum at 500 millibars.
- (iv) Absolute vorticity replaced by f when used as a multiplier.
- (v) The thermal wind in any vertical column is constant in direction and proportional to the thickness.

Basic equations.—The quasi-geostrophic vorticity equation may be written in isobaric co-ordinates as

$$\left(\frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla\right) \left(\frac{g}{f} \nabla^2 z + f\right) = -f \frac{\partial w}{\partial p}. \quad \dots\dots (1)$$

Applying (1) at the levels 500 and 1000 millibars and substituting the assumed profile of vertical velocity, the adiabatic equation can be used to eliminate the unknown vertical velocity at the mean pressure level.

The relevant forecasting equation for z_L , the height of the 500-millibar surface, is

$$\frac{\partial}{\partial t} (z_L - \bar{z}_L - G) = -\mathbf{V} \cdot (\bar{\nabla}_L + G) \cdot \nabla (z_L - \bar{z} - G), \quad \dots\dots (2)$$

where $\mathbf{V}(z_L + G)$ is the geostrophic velocity obtained from the contours of $(z_L + G)$ and G is a function of the Coriolis parameter, chart magnification and length. The second forecasting equation which gives z_0 , the height of the 1000-millibar surface, is

$$\frac{\partial}{\partial t}(z_L - Bz_L - z_0) = \mathbf{V}(z_L - Bz_L) \cdot \nabla(z_L - Bz_L - z_0), \dots \dots (3)$$

where $\mathbf{V}(z_L - Bz_L)$ is the geostrophic velocity obtained from the contours of $(z_L - Bz_L)$, and B varies between 0.62 at 30°N. and 0.38 at 70°N. and has been taken at 0.5 over the whole chart. In obtaining (2) and (3) the vorticity, ζ , has been replaced by the finite difference approximation $\zeta = 4(\bar{z} - z)/d^2$.

The field of \bar{z}_L is obtained by graphical additions of two copies of the z_L field displaced through the appropriate grid length firstly in the x direction and then in the y direction, whence the fields of $(\bar{z}_L + G)$ and $(z_L - \bar{z}_L - G)$ are formed by simple additions and subtraction. From equation (2) the 24-hour change $\Delta(z_L - \bar{z}_L - G) = \Delta z_L$ is obtained by advection of the field of $(z_L - \bar{z}_L - G)$ in the field of $(\bar{z}_L + G)$. Similarly, the 24-hour change in thickness $\Delta(z_L - Bz_L - z_0)$ is given by (3) by advection of the field $(z_L - Bz_L - z_0)$ in the field $(z_L - Bz_L)$, Δz_0 being obtained by using the forecast field of Δz_L .

Discussion.—*Preparation of forecasts.*—Forecasts were made each weekday in the period from 15 October to 9 November 1956 inclusive, a total of 20 forecasts in all. The initial data were obtained from the current 0300 G.M.T. surface and 500-millibar charts, which were usually completed by 0900 G.M.T. Occasionally some alterations were made to the initial charts after 0900 G.M.T. due to the arrival of delayed observations, but these changes could not be incorporated into the forecast once the procedure had commenced.

Owing to lack of familiarity with the operations involved, the first few forecasts took some four or five hours but towards the end of the trial period two people sharing the work could make a 24-hour forecast for 1000 and 500 millibars in about two hours. Each daily forecast involved the use of eighteen sheets of tracing paper of chart size, comprising five for tracing, eleven for graphical addition and subtraction and two for advection.

Accuracy of forecasts.—Correlation coefficients were evaluated between observed and predicted 24-hour changes in the surface pressures and 500-millibar heights. The coefficients were evaluated for both the Central Forecasting Office and Estoque forecasts, and in addition correlation coefficients were found between forecast geostrophic and observed wind at 500 millibars. The 0600 G.M.T. charts were used for the evaluation of the coefficients between the Central Forecasting Office (C.F.O.) forecast and actual 24-hour 1000-millibar height changes. The correlation coefficients were evaluated at three points—Leuchars, ship “I” and ship “J”—and are shown in Table I. It is

TABLE I—CORRELATION COEFFICIENTS BETWEEN ACTUAL AND FORECAST CHANGES

	Surface pressure		500-mb. heights		Southerly component of 500-mb. wind		Westerly component of 500-mb. wind	
	Estoque	C.F.O.	Estoque	C.F.O.	Estoque	C.F.O.	Estoque	C.F.O.
Leuchars ...	0.78	0.88	0.79	0.89	0.73	0.89	0.73	0.91
Ship “I” ...	0.58	0.85	0.75	0.93	0.65	0.74	0.55	0.71
Ship “J” ...	0.54	0.81	0.55	0.78	0.43	0.57	0.75	0.86

appreciated that this is not necessarily the best way to compare charts, but the correlations are presented so that comparison may be made with similar figures presented elsewhere.

A visual comparison of the three sets of charts was made by five experienced meteorologists. Actual charts were also compared with actual charts of the previous day so that some estimate could be made of the value of a forecast of persistence. Areas near the edges of the charts were ignored for comparison purposes—evaluation of \bar{z}_L necessarily removing 1,200 miles from the east-west edges—and marks from zero to ten were awarded for accuracy of forecasts in an area roughly bounded by 35°N., 70°N., 20°E. and 40°W. Particular attention was given to correct forecasts of large changes and new developments. The summary of the marks awarded is given in Table II.

TABLE II—MARKS GIVEN TO ESTOQUE, CENTRAL FORECASTING OFFICE (C.F.O.) AND PERSISTENCE FORECASTS

						Surface	500 millibars
						<i>number of marks</i>	
Possible total	...	...	...	...	...	950	1000
Estoque	...	...	...	...	...	509	594
C.F.O.	...	...	...	...	...	651	720
Persistence	...	...	...	...	...	464	508

The marks and correlation coefficients indicate that the Estoque forecasts made for this period were better than those which could have been obtained by persistence, but worse than the conventional forecasts prepared in the Forecast Division at Dunstable.

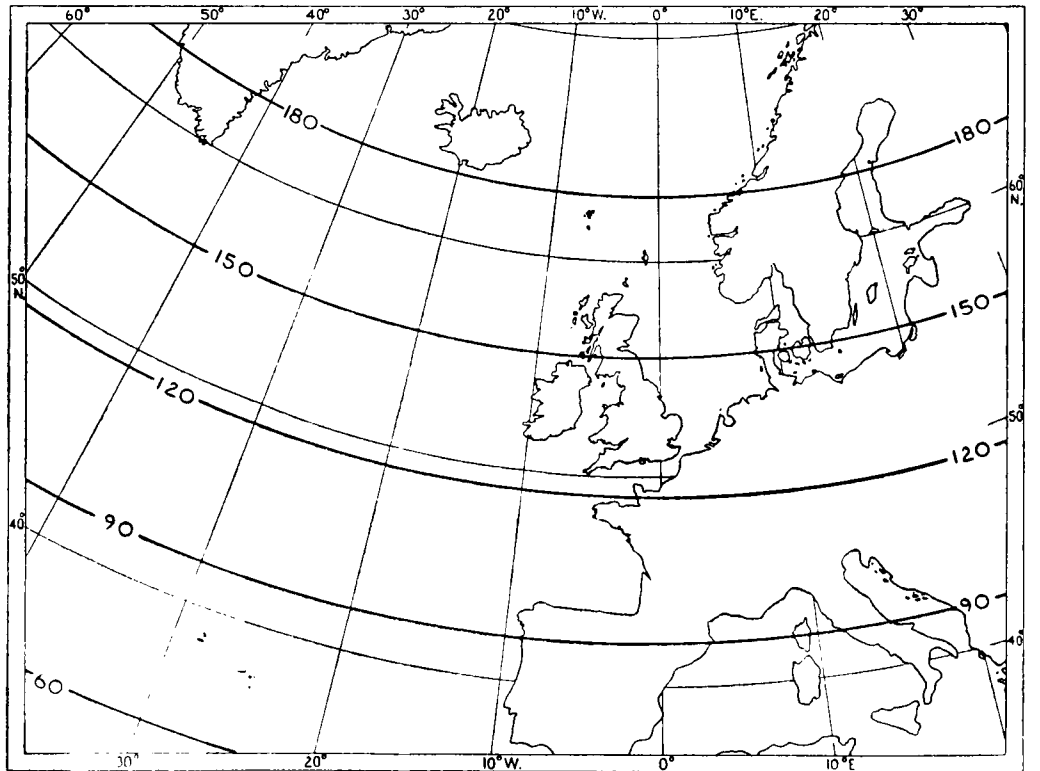


FIGURE I—THE G-FIELD IN METRES

Sources of error.—*Assumptions of the method.*—Estoque² admits that several of the assumptions in the basic theory could, in certain conditions, lead to errors in the forecast, for example, the variation of B with latitude has been neglected so that the value of thickness, $z_L - Bz_L$, used is an overestimate at 70°N. and an underestimate at 30°N. Further, the advecting fields, $\bar{z}_L + G$ and $z_L - Bz_L$, are assumed conservative over 24 hours. Whilst the assumption is a reasonable approximation for the former field (see Figure 2), it is less reasonable for the latter.

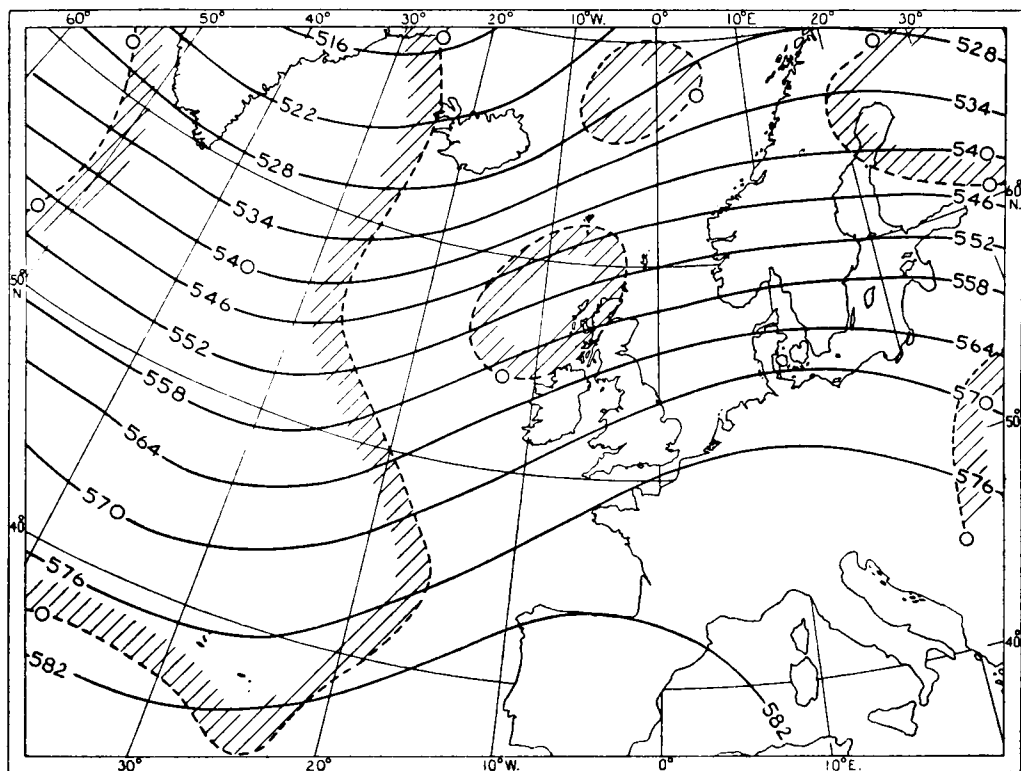


FIGURE 2—THE ADVECTIVE FIELD, \bar{z}_L , AT 0300 G.M.T., 22 OCTOBER 1956 AND THE CHANGE BETWEEN 0300 G.M.T., 12 OCTOBER 1956 AND 0300 G.M.T., 23 OCTOBER 1956

The continuous lines are \bar{z}_L in tens of metres; the broken lines are the change in tens of metres (there was no change exceeding 60 metres); negative change is indicated by hatching on the negative side of the lines of zero change.

Initial data.—The 0300 G.M.T. surface and 500-millibar charts were available for copying by about 0900 G.M.T. each day. Surface observations are considerably fewer at 0300 G.M.T. than at the major synoptic hours, and occasionally significant features were located on the 0600 G.M.T. chart which were not covered by the 0300 G.M.T. observations. This paucity of observations occasionally led to large errors, but in general the increased definition of the chart analysis given by an increase in surface observations probably would not have a significant effect on the final forecast.

At 500 millibars the absence of even one or two observations can lead to important differences in the initial chart and subsequently these differences were often amplified.

Orographic effects.—As in other numerical forecasting techniques the present method of forecasting using the Estoque procedure does not allow orographic influences to be included. On several occasions the forecast at 1000 millibars produced deep depressions over the Greenland ice-cap, whereas the actual charts for the following days showed the movement of the depression along either the Davis Strait or the Denmark Strait. Estoque² indicates that experiments are already in progress which include modifications of the method to take account of orographic effects.

Advection.—The advection of one field in another can lead to considerable errors in the final pattern. Although these errors are to some extent caused by minor irregularities in the contours of the advecting field, the main source of error is the inability of the forecaster to carry out the advection process exactly.

On ten days of the trial period, the Estoque forecasts were made independently by each of the authors. It was found that although the advecting fields obtained were in close agreement, significant differences occasionally arose in the final forecasts which could be directly attributed to the advection process. For example, when the advecting field exhibited strong gradients, minor ridges and troughs at 500 millibars with wavelengths of the order of 500 miles could be as much as 180 degrees out of phase between the two forecasts; when marked diffuences and confluences were present in the advecting field the associated belts of strong winds might be displaced up to 200 miles from one forecast to another. In fact, any marked variations in the gradients of the advecting field could lead to significant differences in final forecasts.

Conclusions.—It is possible for two people sharing the work to produce 24-hour forecasts at 500 millibars and 1000 millibars within two hours of the completion of the analysis of the initial charts. Quantitative and qualitative comparison of the Estoque forecasts with the actual charts and Central Forecasting Office prebaratics showed that the latter are better than the Estoque forecasts, which, in turn, are better than could be obtained by a forecast of persistence. One of the sources of error in the Estoque method is the advection process.

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A THUNDERSTORM AT SHARJAH, PERSIAN GULF, ON 23 NOVEMBER 1957

By R. MURRAY, M.A. and G. A. COULTHARD

A violent thunderstorm, which occurred at Sharjah between 0200 and 0300 hours local time on 23 November 1957 (that is, between 2200 and 2300 G.M.T. on 22 November 1957), produced 74·1 millimetres of rain in approximately 50 minutes and a maximum gust of 57 knots from 030 degrees was recorded. The rather similar thunderstorm of 14 November 1954, reported by Thomas,¹ gave about 56 millimetres of rain in 45 minutes and resulted in considerable

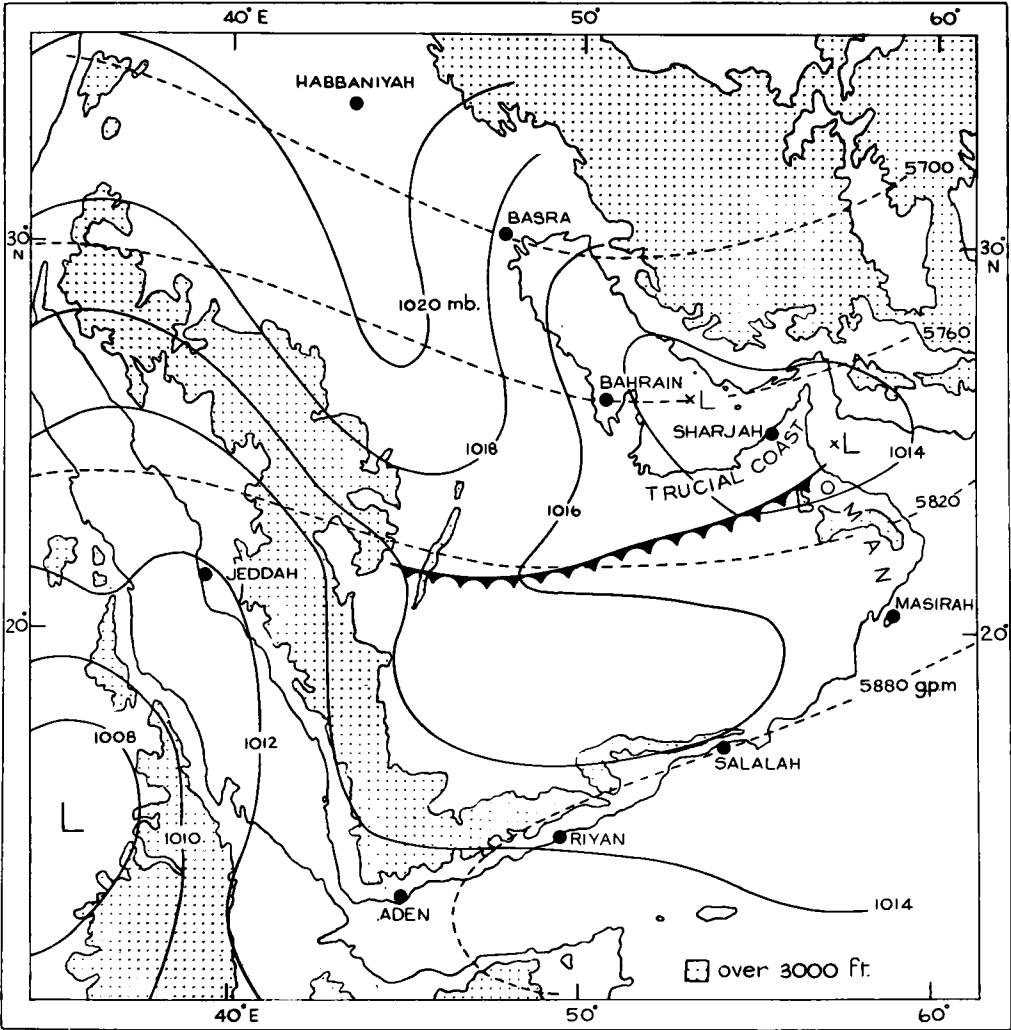


FIGURE 1—SYNOPTIC CHART FOR 0000 G.M.T., 23 NOVEMBER 1957
The broken lines are superimposed 500-millibar contours.

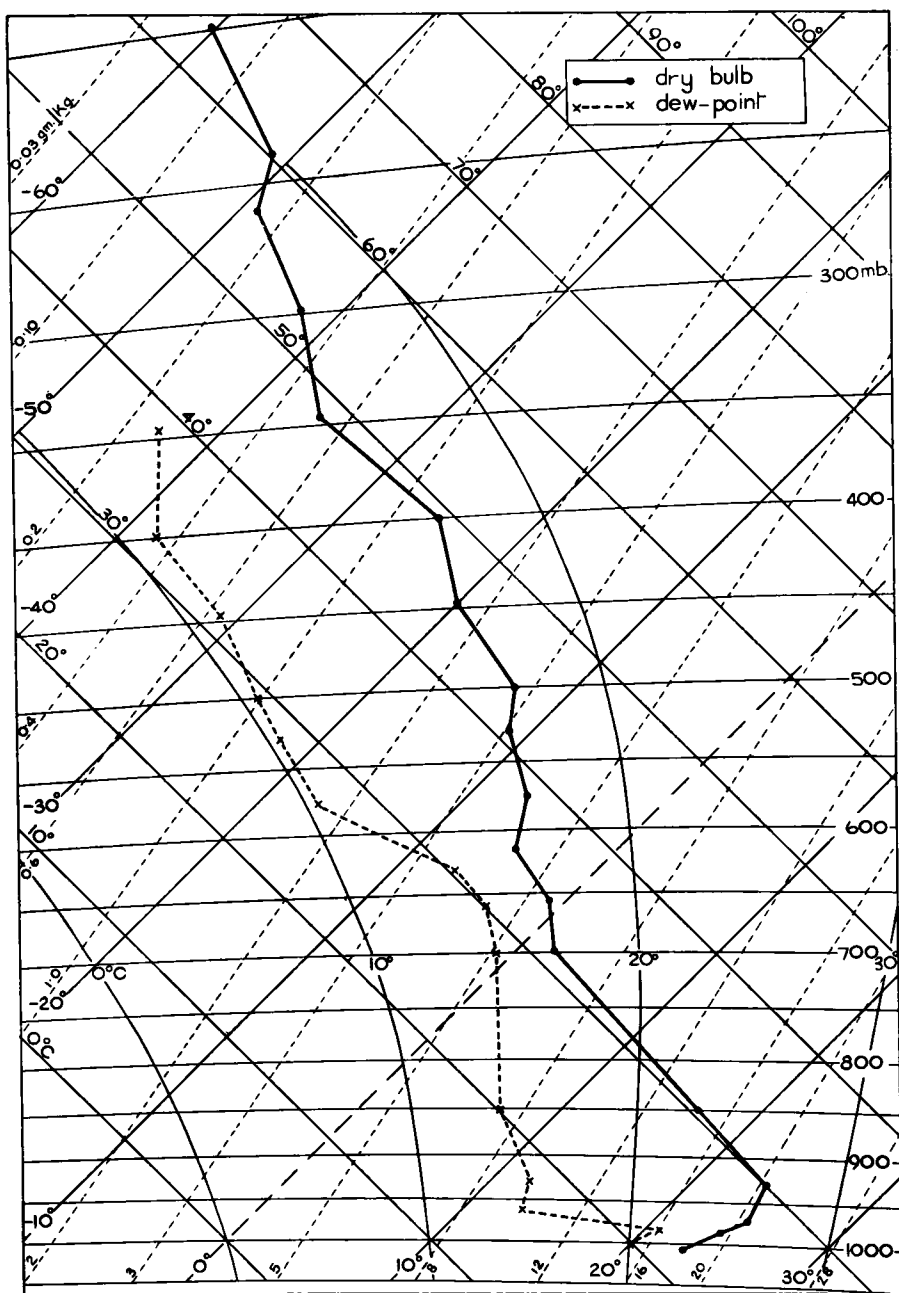


FIGURE 2—UPPER AIR SOUNDING FOR BAHRAIN, 2300 G.M.T.,
21 NOVEMBER 1957

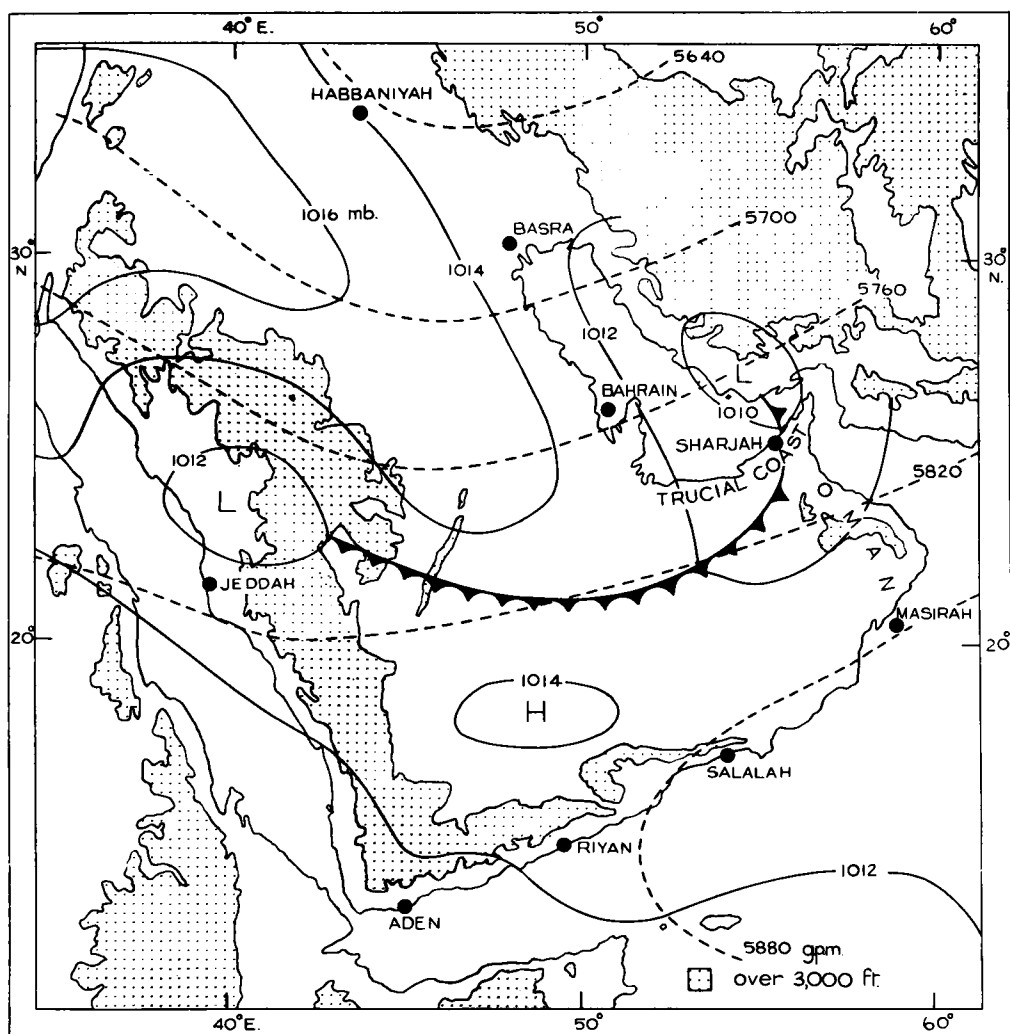


FIGURE 3—SYNOPTIC CHART FOR 1200 G.M.T., 18 NOVEMBER 1957
The broken lines are superimposed 500-millibar contours.

To face p. 177]



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FLOODING AT SHARJAH AIRFIELD AFTER THE THUNDERSTORM ON
23 NOVEMBER 1957

flooding in the camp area. The 23 November 1957 thunderstorm was responsible for much damage, mainly to baroustis and corrugated roofs, in the camp and in the village of Sharjah; and flooding, in places to a depth of 10 inches, was widespread in the camp area. From subsequent reports it appears that the same storm system struck the small township of Dubai on the Trucial Coast some 12 miles to the south-west of Sharjah. At Dubai a number of dhows were beached and one was sunk with loss of life; also two children were killed by hailstones which were reported to be about 15 inches in circumference.

The synoptic situation over Arabia for a few days before 23 November 1957 was uncertain in detail owing to the paucity of observations. In association with a small amplitude upper trough a rather weak surface pressure trough or low developed over north-west Arabia and progressed eastwards with the upper wave. Early on 21 November there was an elongated shallow low pressure system from north-east of Jeddah to south-west Iraq and this system subsequently moved east to south-east. By 0000 G.M.T., 22 November 1957, a low was situated just north of Bahrain; this depression may have developed a double centre (the evidence is inadequate) but undoubtedly the low pressure system as a whole moved east-south-east towards the Trucial Coast and the main features of the synoptic situation are shown in Figure 1. There must have been a good deal of low-level convergence over the Trucial Coast and northern Oman later on 22 November and certainly the air was potentially very unstable in view of the evidence of the Bahrain upper air sounding for 2300 G.M.T., 21 November 1957 (see Figure 2), made when the depression was very near Bahrain. The synoptic situation on 22 November was clearly favourable for thundery rains but the trigger which set off violent thunderstorms in the Sharjah area is not obvious. It is probable that the mountain range to the east of the Trucial Coast was an important factor. However, the precise mechanism is not understood; possibly downdraughts from thunderstorms already set off by uplift over the mountains were instrumental in concentrating low-level convergence near the Trucial Coast and thereby setting off new storms. Unfortunately the Meteorological Office at Sharjah was not open during the critical hours prior to the torrential rain, but it is not uncommon in disturbed weather for lightning to be observed over the mountains of Oman.

The occurrence of severe thunderstorms and heavy rain at Sharjah in November is not exceptional although it is relatively rare and poses a very difficult forecasting problem. For instance, of the seven Novembers from 1951 to 1957 five have had no measurable rain, November 1954 had 68.4 millimetres (most of which fell in the storm of 14 November reported by Thomas¹) and November 1957 had 76.7 millimetres (74.1 millimetres of rain fell in the present storm). It is also of interest to note that in the three weeks or so preceding 23 November 1957 three troughs associated with "western" depressions passed Sharjah (on 5, 9 and 18 November), yet little or no rain was recorded even though at least one of the disturbances, namely that of 18 November (see Figure 3), appeared quite as vigorous as the disturbance of 23 November (see Figure 1), and furthermore the Bahrain upper air soundings suggested that very unstable air was associated with the disturbance of 18 November 1957. Of course heavy rain may have fallen elsewhere over the deserts or mountains of Oman on 18 November. It is perhaps significant that

the troughs of 5, 9 and 18 November 1957, which were inactive in terms of rainfall at Sharjah, were all associated with centres of low pressure which travelled eastwards on a track to the north of Sharjah; whereas the major axis of the depression of 23 November 1957 (see Figure 1), was located just south of Sharjah and the depression of 14 November 1954 was situated south or south-west of Sharjah at the times of the heavy thundery rains.

A mesoscale analysis of "western" disturbances over Arabia and the Persian Gulf would be extremely interesting and illuminating but the observing stations are far too widely separated for this work; indeed the network of reports is often inadequate for analysis of the main features on the synoptic scale.

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METEOROLOGICAL OFFICE DISCUSSION

Hail

The Meteorological Office discussion at the Royal Society of Arts on Monday, 16 February 1959, was on the subject of "Hail". It was opened by Messrs. D. C. Evans and W. G. Harper.

Mr. Evans began by saying that the type of hail under discussion was defined as hard pellets of ice larger than one fifth of an inch diameter and the subject was approached from the aspect of a forecaster dealing with civil aviation. The different theories explaining the formation of hail were summarized briefly and some of the differences of opinion involved were discussed.

Damage to aircraft.—Slides showing damage sustained by aircraft flying in hail over the United States of America were followed by slides showing damage to two B.E.A. aircraft, the first being an "Elizabethan"¹ which was damaged over Lyon at 1507 G.M.T. on 14 August 1954, and the second a "Viscount" which was damaged over Limoges at 1635 G.M.T. on 18 August 1958. The synoptic situations at the surface and 500 millibars on these two occasions were then shown and the similarity of the situations demonstrated. Both surface charts had shallow low pressure centres near the scene of the incidents and both had slow-moving cold fronts associated with these depressions. Both upper air charts were dominated by deep cold troughs to the west of the surface cold fronts and the patterns of the contour and thickness lines were remarkably similar.

In reporting the first incident the hail formation was partially attributed to the uplift over the high ground near Lyon, but in the second case the incident occurred in the lee of high ground. This case was therefore judged to be similar to the most common cases in North America which occur just east of the Rockies, where instability is increased by the break through aloft of colder air from the west of the mountains. Surface and 500-millibar charts for North America² for an occasion of widespread hail damage were shown to be similar to the European situations already discussed. Tephigrams of the ascents nearest to the scene of the two incidents over Europe were shown and the degree of instability of each ascent was discussed.

Review of state of knowledge concerning distribution of hail.—*Northern hemisphere:* Large hail forms mainly in warm, moist, unstable air

masses and is therefore most common in summer. Nevertheless it does not appear to increase in frequency towards the equator but reaches a maximum about 30°N. to 40°N. It was suggested that this distribution is biased by figures coming from surface observations and low-level aircraft reports and may be proved wrong by high-flying aircraft. Alternatively, the bias may be explained by the fact that land areas are at a maximum between 30°N. and 40°N. and hail appears to be much less frequent over the sea than over land.

Frequency of damage to aircraft: In the past five years there have been only seven cases of major hail damage to B.E.A. aircraft. B.O.A.C. report that only one case of severe hail damage has occurred in about every 30,000 hours of flying by aircraft of the Argonaut and Constellation fleets. The fleet of Comet I aircraft flew a total of 25,000 hours and only one incident of hail damage occurred and this at a low level, between 2,000 and 12,000 feet on a climb away from Rome.

Association with thunderstorms: In the central states of the United States of America, United Airlines³ found that hail of one inch diameter or larger occurred in only one out of every 800 thunderstorms flown through. Of these large hailstones, 50 per cent were one to two inches in diameter, 40 per cent two to three inches and 10 per cent were larger than three inches in diameter.

Thunderstorms in the north of North America apparently produce hail more frequently than those in the south. It was suggested that this might point to an essential difference as regards hail formation between air mass and cold front thunderstorms as active cold fronts in the south are rare in summer, when air mass thunderstorms are frequent. However, this variation may be caused by hail melting before reaching the ground in the south, as the United States Thunderstorm Project⁴ reported the same proportion of hail in thunderstorm traverses between 10,000 and 20,000 feet over Florida as over Ohio. In spite of this association of hail and thunderstorms, Ludlam⁵ has suggested that hail is more likely to develop in a developing rather than a mature storm.

Height of hail encounters: Reports are now being received of hail damage up to 30,000 feet,⁶ whereas a few years ago a height of 20,000 feet was thought to be remarkable.

Size of hailstones which damage aircraft.—Slides were displayed showing results of tests designed to measure the damaging effect of hail.³

Forecasting hail.—At present a forecaster usually links the severity of hail with the severity of the thunderstorms expected and cannot attempt to be any more precise but two papers by American meteorologists have given techniques for forecasting the size of hailstones. The earlier method⁷ was described and some of the differences of the later method⁸ were demonstrated. The results obtained by applying the methods to the ascents shown earlier were quoted. The association of hail and tornadoes⁹ was mentioned as the ascent used to demonstrate the hail triangle method resembled the "mean tornado sounding".¹⁰

The future.—New types of aircraft are expected to be more susceptible to hail damage and therefore more research into the problems of hail forecasting is required. Updraught speeds in convection cloud will have to be forecast and the relationship between these speeds and the size of the hail produced must be established. Ludlam¹¹ has suggested that the concentration

of ice nuclei might have a bearing on hail size and this requires clarification. The fitting of search radar equipment to aircraft appears to be the most promising way of avoiding damage by hail and may be more reliable than the best attainable forecast.

Advice to forecasters and pilots.—Until such time as forecasts of hail can be replaced by complete radar guidance, forecasters should realize that hail forms in a deep super-cooled layer of cloud of high liquid-water content, associated with strong updraughts. These conditions, of course, do not always produce hail and even when it does occur, it falls in very small areas at a time. Cold fronts, troughs and high ground add to the probability of hail formation and the type of synoptic situation shown in the slides should be treated as one of potential danger for hail especially in late spring or summer.

Advice to pilots was quoted from the Technical Note³ on hail which described the stage in the life cycle of a thunderstorm which was considered to be most dangerous. The comment was made that the recognition of this stage became difficult when storm clouds are closely bunched together or when other types of cloud obscure the dangerous ones but in these conditions airborne radar appears to make it possible to avoid flying into the active cells of a thunderstorm and the associated hail.

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Mr. W. G. Harper of the Radar Research Station, East Hill, opened the second part of the discussion with a brief description of the work of Schumann¹ and Ludlam² on the heat balance of the hailstone and the stages of wet and dry growth resulting in a layered structure, and also of the work of Bilham and Relf³ in computing the terminal velocities of hailstones from aerodynamical considerations, from which an effective limit to their size was obtained at diameters between 10 and 12 centimetres. The largest hailstone recorded in the United States, which fell at Potter, Nebraska, in 1928 and was of diameter 14 centimetres and weight $1\frac{1}{2}$ pounds, was quoted as being reasonably close to the Bilham and Relf limit.

These represented considerable advances in our knowledge, but surprisingly little is yet known of the relationship of hail to the stage of development of

cumulus and cumulonimbus clouds, and to the occurrence of lightning in them, despite the fact that some current theories of thunderstorm electrification require the presence of hail or graupel.

The study of hail and thunderstorms in June and July 1957 at the Radar Research Station, in which we co-operated with Mr. F. H. Ludlam, of Imperial College, was an attempt to answer some of these questions, and also provided material for studies of the propagation and of the localization of storms. Plan-position radar records were maintained at three-minute intervals, and as many storms as possible were studied on range-height radar, though we had no knowledge at the time as to whether or not they had hail in them. Voluntary observers within a radius of 100 miles reported 330 occurrences of hail, spread over 12 days of storm. 70 per cent of these occurrences were within 70 miles, that is, within half the area. Observers were asked to record times to an accuracy within three minutes and to underline them if they could confirm this. Many did so. Of the 330 occurrences, 298 were of hail the size of peas or smaller (assumed limit one centimetre diameter), 27 were larger than peas and up to the size of cherries (assumed limit two centimetres diameter), and 5 were of hail the size of golf-balls (limit four centimetres diameter). Unfortunately the latter all occurred on one day, a Sunday, for which there are no radar records. The material available for analysis thus mostly relates to small hail.

Analysis of duration of hail-fall at a point.—251 durations of hail-fall were recorded and are analysed in Figure 1. The most frequent duration of fall was two minutes, and almost 50 per cent of the total were three minutes or less. Five which exceeded 30 minutes were probably periods of intermittent hail and rain involving more than one storm cell, and these have been excluded from the main graph and from the means, but are included in the inset graph. The average for these 246 cases was 5.6 minutes, while for 23 cases of hail larger than peas it was 9.2 minutes. There is an interesting tendency, very evident in

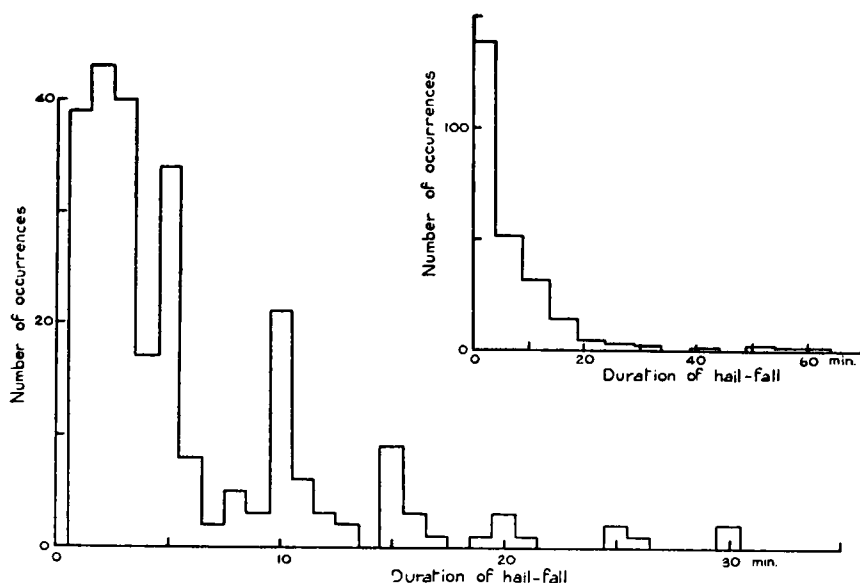


FIGURE 1 — ANALYSIS OF THE DURATION OF HAIL-FALL IN 251 STORMS IN SOUTH-EAST ENGLAND IN JUNE AND JULY 1957

Single reports of durations of 40, 50, 51, 59 and 60 minutes are excluded from the main graph. The inset graph analyses the same reports in five-minute steps.

Figure 1, for some observers to round off their durations to the nearest five minutes. The inset graph removes these irregularities by using steps of 1-4, 5-9, 10-14 minutes, etc.

Obviously storm movement is a factor in the duration of hail at a point. To study this the data were subdivided on the basis of the prevailing 700-millibar wind, as representing an approximate measure of the movement of the storms. In 97 cases when the 700-millibar wind was less than 10 knots the average duration was 6.4 minutes, for 98 cases with winds between 10 and 20 knots it was 5.6 minutes, and for 51 cases with winds greater than 20 knots (actual average close to 30 knots) the average duration was 4.3 minutes. This rather small variation suggests that the reported duration of hail is related more closely to the growth process than to movement. If the effect of storm movement could be removed the figures suggest that the average duration of hail (one centimetre diameter) might be 7 minutes.

Rate of growth of hail.—The main analysis involved the enlargement and examination of plan-position indicator (PPI) radar records at three-minute intervals. Many occurrences proved to be associated with complex long-lived storm masses, but in a substantial number the storm could be traced back to its first detectable echo. It is now generally accepted that this initial echo, for centimetric radar working at moderate ranges, is received from the first precipitation particles of about raindrop size, roughly one to one and a half millimetres in diameter. Since with a filled beam the intensity of the signal increases as the sixth power of the drop diameter, but decreases only as the square of the range from the radar, a relatively small variation in drop size ensures detection over quite wide limits of range. This justifies us in considering the time intervals between first detectable echoes and hail reaching the ground without regard to range. These were analysed, and showed a pronounced maximum around 15 to 20 minutes. 61 out of a total of 158 cases were of time intervals between 10 and 25 minutes, average $17\frac{1}{2}$ minutes. With PPI photographs at three-minute intervals the true initial echo may have been up to two minutes earlier than that recorded, and we therefore correct this to $19\frac{1}{2}$ minutes. Of course some timing errors by voluntary observers are to be expected, but a majority of the 61 observers were well-placed, with times underlined to confirm their accuracy.

Hail of diameter one centimetre would have a fall-speed between 10 and 15 metres per second, depending on density, and would take two to three minutes to fall from a typical summertime freezing level in south-east England. This leaves 17 minutes for growth from diameter about one millimetre to one centimetre.

It must be added that there was an extended tail of long time intervals which in general represent the more complex storms. Long time intervals are not necessarily evidence that the hail-forming process is itself a long one. It is possible that the hail in complex storms actually grows in young and active cells embedded in the storm mass. Frequently in the records the hail occurred near clear-cut edges of echo rather than at the centres of the echo masses.

Elmdon storm, 19 July 1957.—A particularly well authenticated example of rapid development in a hailstorm was that recorded at the Meteorological Office at Elmdon on 19 July 1957. The Liverpool 1100 G.M.T. upper air

sounding was probably typical, being very moist up to 700 millibars, and suggested convection almost without hindrance up to the tropopause at 30,000 feet. Indeed an echo top to this height was recorded before 0900 G.M.T., and echo tops in the range 30,000 to 34,000 feet were measured frequently throughout the day, which produced 86 reports of hail, by far the greatest number on any day of our study. The storms had greatly decreased by 1800 G.M.T., but just after 1900 G.M.T. a very active development took place within a mile of Elmdon (Figure 2).

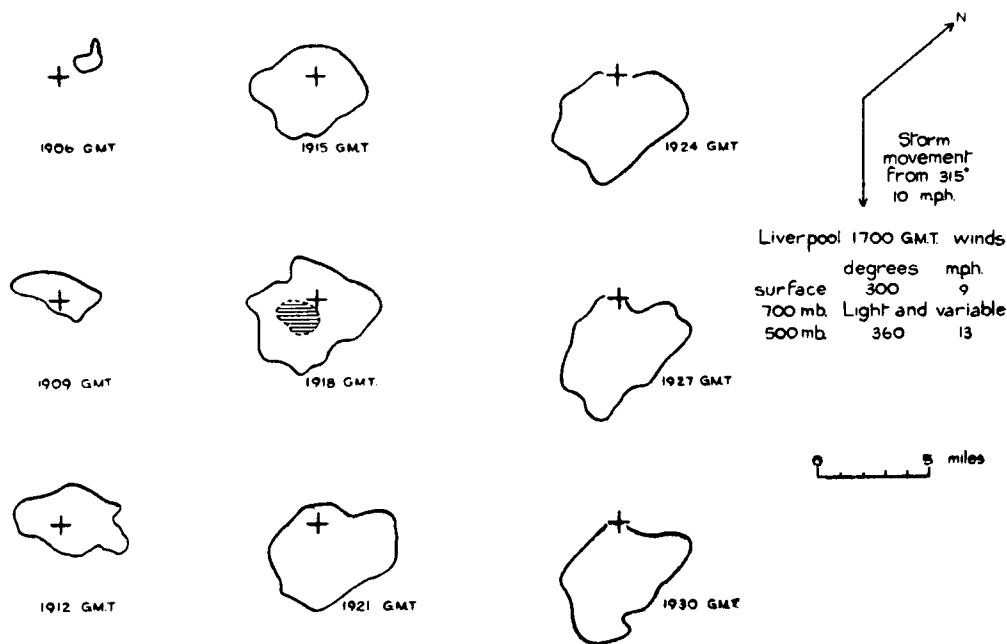


FIGURE 2—THE REMARKABLE DEVELOPMENT OF THE ELMDON STORM ON 19 JULY 1957

The echo pattern is shown at 3-minute intervals. Hail of cherry size fell for 19 minutes from 1916 to 1935 G.M.T., and the first lightning discharge occurred at 1915 G.M.T. The storm movement is in good agreement with the average wind between the surface and 500 millibars. The crosses mark the observing site.

It must of course have been a substantial cloud some time before the first echo appeared at 1906 G.M.T., but within twelve minutes it had reached its maximum size of about 20 square miles. The observer kept detailed observations, with times underlined. He recorded first lightning in the storm at 1915 G.M.T. Hail (15 millimetres in diameter) fell only one minute later at 1916 G.M.T. and lasted for 19 minutes. Allowing two minutes for a possible initial echo at 1904 G.M.T., this gives an interval for growth and fall of only 12 minutes. The highest echo top recorded in it was 32,500 feet at 1916 G.M.T., the precise time of onset of the hail.

The open-time-scale rain recorder at Elmdon shows that the hail was not mixed with rain at first. This is a common feature in hailstorms. Slight melting shows on the trace from 1920 G.M.T., but from 1922 G.M.T. heavy rain was mixed with the hail. This can be the only interpretation of the very sudden change of slope of the record. The maximum rate of fall was two millimetres per minute, and there was a total fall of 12.5 millimetres in 20 minutes. The lag

between hail and rain, in this case six minutes, may be indirect evidence of a drop-shedding process in the cloud. Ludlam² has shown that excess water from the wet stage of hail growth is shed in the wake of the stones as water-drops. These are unlikely to be infected by freezing nuclei, and probably grow rapidly as raindrops. Assuming 15-millimetre hail and 3-millimetre drops, a lag of six minutes could be explained by differential fall velocities from about the 5000-metre level, a plausible region for active hail growth, the temperature there being -18°C .

Occurrence of first thunder.—The accurate reporting of hail was made the first priority but our observers were asked, if they could, to keep records of thunderstorms, including whether or not hail occurred, the interval between flash and thunder, and their directions. Absence of mention of thunder cannot be interpreted as meaning that it did not occur but, in all, 78 reports of first thunder associated with hailstorms were received. 60 per cent were within five minutes of the onset of hail. On average the first thunder was two and a half minutes before the onset of hail. Since, as we have seen, the hail takes two to three minutes to fall from the freezing level, this suggests that the first discharge is, on average, coincident with the completion of the growth process of the hail, that is, when the hail has reached the freezing level in its fall. As we have mentioned, some theories of thunderstorm electrification^{4,5} require the presence of hail or graupel. We have no evidence from this study that hail must be present for the generation of lightning. Hail seems to be too infrequent for this to be the case.

Hail without thunder.—On a few occasions observers were definite that thunder did not occur when hail fell. In one storm three independent observers reported small hail of a few minutes' duration, and all three stated that there was no thunder. Echo tops at this time had not been seen to exceed 16,000 feet. Half an hour later, however, thunder was reported from a station ten miles distant, and the highest echo top of the day, 22,000 feet, was recorded in this. There is reason for thinking that the storm was only marginally giving thunder, since the temperature at the 22,000-foot level was only -30°C . Jones⁶ has reported that the warmest temperature at a cloud top associated with thunder was close to -30°C . No evidence was found of larger hail falling in the absence of thunder.

Rapid development of hail.—Mr. Harper thought it was important that those who had access to radar displays at airfields (for example, airfield controllers) should be aware of the rapidity of development of some of these storms. In the time an aircraft might take to taxi and run up its engines substantial hail can develop where there was no previous echo. The work at East Hill had shown that many of these hailstorms were associated with the active stage of cumulus and cumulonimbus growth, and often with quite young clouds. He stressed, however, that the storms studied were not of the violence experienced in other countries. In Italy in 1958 they had found that storms of mature appearance may yet have violently growing cells and damaging hail in them. Support was given to this by the work of Donaldson,⁷ who had found a 50 per cent frequency of hail occurrence in storms reaching 46,000 feet in New England.

Propagation and localization of thunderstorms.—Mr. Harper showed slides of an interesting case of the propagation of a large area of thunderstorms

in a direction unrelated to the prevailing winds, which occurred on 4 July 1957. He suggested that this was caused by a local convergence effect operating on one side of the storm mass, and showed evidence for a convergence line of this type on the edge of a cumulonimbus. Mr. Harper also presented a study by Mr. Ludlam of a large-scale effect of convergence on 18 June 1957, another day of their study. The development of a line of thunderstorms extending from north-west London to Salisbury, and a second line inland from the Hampshire and Sussex coasts, were shown to be associated with marked convergence in the surface winds (the latter clearly a sea-breeze effect). It is hoped to publish more detail of these studies elsewhere.

The *Director-General* thanked the two speakers and invited Mr. Ludlam to start the discussion.

Mr. F. H. Ludlam, Imperial College, gave further details of the work carried out by Mr. Harper and himself in Italy, which necessitated some revision of theories of hailstone growth. The more important conclusions were:

- (i) that a typical hailstorm begins its life as a modest rainshower;
- (ii) that after the rain formation successive cloud towers attain higher ascent speeds, and rise to ever higher peak heights;
- (iii) that the increase in the updraughts cannot be explained except by calling upon additional release of energy, and that this is provided as latent heat of fusion during the growth of the hail;
- (iv) that large hailstones must complete their growth in big glaciated towers, most of whose condensed water is frozen;
- (v) that large stones become wet even in small liquid-water concentrations, and probably in addition assimilate small ice particles; for this reason the wet stage may not impede growth to the extent that was formerly thought;
- (vi) that large hailstones fall in small concentrations (much less than one per cubic metre) not because embryo hailstones are rare, but because only a few of them remain in the cloud long enough to reach a very large size.

Mr. E. Chambers, B.O.A.C., said that, in spite of the few encounters with severe hail and the success of radar methods of avoiding hail, we could not be complacent and certain important questions arose:

- (i) What effect will hail damage have on new types of jet aircraft, which may be more susceptible to damage, not only because of increased air-speeds, but also because the shape of the exposed surfaces may be more critical aerodynamically?
- (ii) What amount of engine damage will result? He was surprised by the small size of hailstones mentioned because he had read of hail of much larger diameters.

He pointed out that search radar equipment carried by aircraft had proved highly successful in practice. Since D.C.7C's had carried this equipment there had been no encounter with hail. He regarded it as essential that forecasters should give as detailed a warning of hail as possible, including the likely size of the hailstones, in pre-flight briefings.

Captain Frost, B.O.A.C., spoke of his experiences with United States radar equipment installed in D.C.7C aircraft and said that, thanks to it, he had been

able to avoid hail cloud. He recounted an incident in which he was involved with hail cloud and referred specifically to the enormous vertical currents encountered at about 17,000 feet. In closing, he added that he had ascertained from some of the B.O.A.C. pilots that none had experienced hail above 20,000 feet.

Mr. Veryard asked what degree of success was attained by the United States techniques for forecasting the size of hailstones.

Mr. Evans then said that the Americans claim an 85 per cent probability of success in forecasting the size of hail and, in reply to a further question from *Mr. Veryard*, said that this success was not claimed for forecasting the occurrence of hail, but only for forecasting its size when it did occur.

Mr. Wallington said that the experience of glider pilots suggested that a shear of $2\frac{1}{2}$ knots per 1,000 feet or more disrupts thermals below cloud base, and asked if cloud thermals were destroyed by shear in the same way. In reply, *Mr. Ludlam* said that so far from a strong shear breaking up large cloud thermals it appeared to him that the worst storms were usually associated with strong shear. He agreed with *Mr. Harper* that some shear would be required to explain the production of large hailstones, because it was necessary that only a proportion of the stones in one thermal should be transferred to a succeeding thermal; if the thermals rise in a vertical column this would not be possible.

The Director-General said that peculiar radar echoes had been reported from tornadoes. He was surprised to hear that large hail was associated with tornadoes because he had understood that they were relatively shallow. *Mr. Ludlam* replied that probably the large hail did not fall in the immediate vicinity of the tornado, but mentioned that a recent radar photograph from America had shown a tornado to extend to 30,000 feet.

Mr. Sawyer asked if the very strong updraughts required for hail growth could be accounted for solely by the buoyancy of the cloud air. *Mr. Ludlam* said that the speed of rise of cloud thermals was proportional not only to the buoyancy but also to the size of the thermals. Well above the ground, where thermals might be as much as two or three kilometres across, very strong updraughts could result from excess temperatures of as little as 1 to 2°C.

The Director-General asked if hail and rain could be differentiated on the radar screen. *Mr. Harper* did not think that this was generally possible, but said that they had recorded echo intensities of very great power in storms in Italy, in excess of anything they had recorded in England; these represented impossibly high rates of fall, as rain, and could only be explained as containing hail. Some of these storms were proved to have damaging hail in them, but it was not possible to determine whether every such intense echo was associated with hail. On theoretical grounds it seemed that it must be so.

Mr. Chambers mentioned the "hooked fingers" which had been reported from America as being associated with hail, and asked whether different shapes of response on radar screens were linked with different kinds of precipitation. *Mr. Harper* replied that peculiar shapes could often be seen in the echoes from decaying storms, but they had not seen any peculiarities of high intensity which could be interpreted as indicators of hail.

Capt. Frost mentioned that American airborne radar equipment fitted in some of their B.O.A.C. aircraft had an iso-echo contour device which showed up the intense cores of storms as black centres to the echoes. This gave the impression of "hooked fingers". The device enabled them to differentiate readily between ordinary and heavy precipitation.

The Director-General in closing the discussion said he was pleased to see this use of radar in modern meteorology, but expressed astonishment at the units employed in the study of hail, for example, the pea, the cherry and the orange! He thanked the authors, the visitors and other speakers for the very interesting discussion.

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OBITUARY

Dr. W. R. G. Atkins, C.B.E., F.R.S.—It is with regret that we record the death on 4 April 1959 at the age of 74 after an illness lasting several months, of Dr. W. R. G. Atkins, C.B.E., F.R.S., who served in the Meteorological Office during the Second World War.

Dr. Atkins, who was born at Cork in 1884, was Head of the General Physiology Department of the Marine Biological Laboratory at Plymouth for more than thirty years. During this period he published a large number of papers, many of them concerned with the problems of illumination and penetration of light in the sea. His expert knowledge of these problems fitted him well for his war-time work in the Instruments Division of the Meteorological Office on the measurement of visibility and of daylight illumination. This work was described in a number of *Meteorological Research Papers* and led to the development of the photo-electric visibility meter and daylight illumination recorder.

Dr. Atkins was appointed O.B.E. in 1919 and advanced to C.B.E. in 1951. His election to the Fellowship of the Royal Society took place in 1925 and he was awarded the Boyle Medal of the Royal Dublin Society five years later. He was a man of great charm and those members of the Meteorological Office who were associated with him at Stonehouse during the war will have pleasant memories of his delightful Irish humour. Our deepest sympathy goes to his widow and to his son in their bereavement.

F. J. SCRASE

METEOROLOGICAL OFFICE NEWS

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

Mr. G. B. K. James, Experimental Officer, who retired on 29 April 1959. He joined the Office in March 1927 after service with the Royal Fusiliers in the First World War and in the Royal Air Force from 1920 to 1926. Apart from two periods at aviation outstations from 1927 to 1930 and from 1940 to 1945 his service was spent at Headquarters in the Forecasting, Climatology, Aviation Services and Physical Research Divisions. From 1957 until his retirement he served in the assistant directorate for Observatories and Micrometeorology.

REVIEW

Über Land-und Seewinde an der Küste der Insel Usedom und ihre bioklimatische Bedeutung. By Helmut Zenker. Abhandlungen des Meteorologischen und Hydrologischen Dienstes der Deutschen Demokratischen Republik. Nr. 44. 11¼ in. × 8 in., pp. 72, *illus.* Akademie-Verlag, Berlin W.8, Monrenstrasse 39, 1957. Price: DM 21.50.

The author has made a synoptic study of eleven sea-breezes occurring during 1953 on the island of Usedom in the Baltic and examined their effect on the climate on the beach. His observations of wind, air temperature, humidity and concentrations of dust and salt nuclei were made from a 15-foot high sand dune. Sea temperatures were also taken. He finds three main categories of sea-breeze: (i) With weak initial gradient wind and convection, the sea-breeze increased steadily up to Force 4 or 5 during the afternoon and then fell off quickly; (ii) with weak initial gradient wind and stable conditions, the breeze set in earlier and reached only Force 2 or 3; (iii) with a stronger offshore gradient wind, a sudden change to a sea-breeze occurred at about midday. The associated temperature and humidity changes are as one would expect, the air becoming cooler and moister with the onset of the sea-breeze, but less perceptibly so in case (ii). The onset was accompanied by a decrease in dust concentration and an increase in salt content.

To measure the amount of comfort or discomfort experienced by health-seeking East Germans lying exposed on the beach, the author evaluates a rate of cooling according to the formula $(36.5 - T_{\text{air}})(0.26 + 0.34V^{0.622})$. The comfortable values are those between six and twelve; for values less than six it is too hot and greater than twelve too cold. The sea-breeze is shown to maintain pleasant conditions on the beach during the summer when it is too hot inland.

To the reviewer it seems that the value of the work to the physical meteorologist is limited by the restricted nature of the observations, only one station being used. Also little or no physical discussion of the various results is attempted. The method of measuring the physiological effects of sea-breezes is interesting, although direct solar radiation is neglected. One suspects that a similar analysis would provide less flattering results if applied to sea-breezes at our own holiday resorts.

R. P. PEARCE

BOOKS RECEIVED

The investigation of atmospheric pollution. Research and observations in the year ended 31st March, 1957. Thirtieth report by the Department of Scientific and

Industrial Research. 9½ in. × 6 in., pp. iv + 136, Her Majesty's Stationery Office, 1959. Price: 7s. 6d.

Le compteur d'orages suisse. By J. Lugeon et J. Rieker. (Reprinted from *Annalen der Schweizerischen Meteorologischen Zentralanstalt*, 1957.) 12 in. × 8½ in., pp. 7, *illus.*

NOTES AND NEWS

Lightning photographs, 5 September 1958

The prints of the photographs of lightning published in the December 1958 number were sent to Dr. B. F. J. Schonland for his opinion. He considers that the upward branched flashes were not associated with a tall building, as suggested in the Magazine, but that they originated in the cloud and are discharges from a negative centre to positively charged areas in the air or another part of the cloud base.

Orographic waves over Malta

In the January 1959 *Meteorological Magazine* part of the caption under Plate II should read "the wind is blowing across the photograph from right to left" instead of "from left to right".

WEATHER OF FEBRUARY 1959

Northern Hemisphere

Cyclonic activity throughout the month was unusually intense over the North Atlantic from Newfoundland to Spitsbergen and Novaya Zemlya. Many deep depressions moved along this track and extremely rapid development of small wave depressions was observed on a number of occasions. The mean pressure chart showed one low pressure centre close to Cape Farewell (the usual position of the Icelandic low) and another over Spitsbergen, the anomalies at the centres being — 14 millibars and — 19 millibars respectively. An associated area of negative anomalies extended over the north-west Atlantic and all parts of the Arctic. Nearly everywhere in Europe (apart from Iceland and Spitsbergen) mean pressures were above normal. The maximum was over central Europe where the unusually high value of 1034 millibars was attained, but the largest anomaly, + 19 millibars, occurred over the North Sea.

The Aleutian low was less intense and further north than usual so that although the North Pacific high was nearly normal in all respects, positive pressure anomalies of up to 12 millibars were recorded over most parts of the North Pacific. The centre of the Siberian high was near normal in position and intensity but mean pressures were below the average over the Caspian Sea and the Urals, anomalies of up to — 8 millibars occurring. Pressure anomalies over North America were small.

Mean temperatures were 7° or 8°C. above average in northern Scandinavia, and smaller positive anomalies occurred over southern Scandinavia, Iceland and north-west Russia. Over much of Britain and central Europe temperatures were near average but they were 2° to 6°C. below average over Turkey, the eastern Mediterranean and Iraq. Persistent strong northerly flow caused negative temperature anomalies over eastern Canada which were as much as

— 7°C. in central Quebec. It was warmer than usual, however, in western Canada and Alaska where anomalies of + 3°C. occurred over a wide area and + 5°C. was reported in places. Further positive anomalies of a similar magnitude occurred in Mongolia and Japan. It was generally slightly cooler than usual in the United States of America.

Deficiencies of rainfall occurred in most parts of Europe, many stations having less than 30 per cent of their normal amount and some none at all, a very abnormal occurrence in February. More precipitation than average was recorded at almost all stations in the Arctic, and the increased cyclonic activity and strong south-westerly flow over the Norwegian Sea was marked by high precipitation totals in Iceland and along the west coast of Norway. Much of Canada had a deficiency of precipitation, while in the United States of America amounts were generally above normal, reaching twice the normal in some places in south-eastern states. Extensive flooding of the Wabash River in Indiana followed one period of heavy rain and many evacuations were necessary. On 10 February a tornado struck St. Louis causing much damage and many deaths.

WEATHER OF MARCH 1959

Great Britain and Northern Ireland

Weather during the first week of the month was dominated by vigorous depressions to the west and south-west of the British Isles, while during the second week, troughs from the Atlantic moved slowly across the country. A belt of high pressure extended from Europe across the British Isles from the 16th to 21st, but thereafter persistently cyclonic weather over the Atlantic spread eastwards to give changeable weather over the country during the remainder of the month.

An anticyclone, centred near the southern Baltic, maintained a southerly air stream over the south and east of the British Isles during the first two days of the month and the weather was generally warm and sunny after the clearance of fairly extensive early morning fog: temperature rose to 64°F. at several places on both days. March 2nd was the fourth successive day with temperature in excess of 60°F. in parts of south-east England. A vigorous depression, moving north-east from our south-west approaches, filled rapidly over southern England and gave widespread and locally heavy rain on the 3rd. The following day an exceptionally deep depression, with central pressure about 943 millibars, became situated off western Ireland and there were severe gales to the south-west of the British Isles, but the depression filled rapidly as it moved east. Wind reached gale force locally along our western seaboard—a gust of 50 knots was recorded at the Lizard on the 5th—and weather was cloudy with rain or showers and scattered thunderstorms until the 7th when this depression also filled up over southern England, and winds moderated generally.

On the 7th an intensifying ridge of high pressure spread quickly from Greenland towards the British Isles and associated northerly winds brought scattered snow showers to Scotland. The next day an anticyclone, which had formed off northern Scotland, moved south-east across the North Sea and winds over the country veered to east, weather becoming generally cloudy although in some western districts the cloud broke up to give prolonged sunshine. High

pressure became established over Russia from the 10th to 14th and active troughs from the Atlantic moved slowly north-eastwards across the British Isles bringing milder but changeable weather with rain to most places, particularly in the west, although there were good sunny periods on the 11th and 12th.

A week of settled weather began on the 15th as an anticyclone to the west of Ireland moved slowly north-eastwards to link with the European high pressure system. A renewal of easterly winds on the 18th caused a marked fall in temperature, and there were ground frost and fog patches during the early mornings in many places; light snow showers occurred in eastern England, but the weather was predominantly dry with good sunny periods.

Milder air from the Atlantic spread over the country from the south-west on the 22nd bringing fairly general rain or drizzle and, in the late evening, widespread fog which also affected the English Channel and the North Sea. Afternoon temperatures outside foggy areas reached 60°F. at many places. A trough from the Atlantic moving east across the country on the 24th, accompanied by a belt of rain, was a prelude to a succession of such troughs in the south-westerly airstream which persisted over the country for the remainder of the month. Weather was mild and changeable with occasional rain or showers alternating with brighter periods. There were thunderstorms in places. On Good Friday and Easter Saturday, the 27th and 28th, weather was showery with long sunny periods, but there was rain in most places on Easter Sunday and early Easter Monday as a depression off north-west Ireland moved south-eastwards to north-east France and filled.

Mean temperatures for the month were everywhere above average but, although some places in the west and south were sunny, it was dull over much of the country. The general rainfall was over England and Wales 115 per cent, over Scotland 89 per cent and over Northern Ireland 123 per cent of the 1916-50 average. Less than half the average fell over eastern Britain from Tees-side to the Firth of Forth and in the Spey valley. Twice the average was exceeded in the Vale of Taunton and over much of the upper Thames valley.

The warmer weather favoured spring growth in eastern areas, apple and pear trees being especially forward. In the west, however, the wet ground often held up outside work, and crops on the whole were a little backward. There was good leaf growth on soft fruit, but glass-house tomatoes suffered from the reduced sunshine.

WEATHER OF APRIL 1959

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

	AIR TEMPERATURE			RAINFALL		SUNSHINE
	Highest	Lowest	Difference from average daily mean†	Per-centage of average*	No. of days difference from average*	Per-centage of average†
	°F.	°F.	°F.	%		%
England and Wales ...	71	20	+2·3	131	+2	99
Scotland ...	69	21	+1·7	123	+3	96
Northern Ireland ...	62	28	+1·1	122	+2	104

*1916-1950

†1921-1950

RAINFALL OF APRIL 1959

Great Britain and Northern Ireland

County	Station	In.	*Per cent of Av.	County	Station	In.	*Per cent of Av.
<i>London</i>	Camden Square Gdns.	2·14	109	<i>Pemb.</i>	Maenclochog, Ddolwen B.	4·85	132
<i>Kent</i>	Dover	3·18	157	<i>Cards.</i>	Aberporth	3·31	139
"	Edenbridge, Falconhurst	2·45	106	<i>Radnor</i>	Llandrindod Wells ...	3·88	147
<i>Sussex</i>	Compton, Compton Ho.	3·11	123	<i>Mont.</i>	Lake Vyrnwy	5·02	124
"	Worthing, Beach Ho. Pk.	2·16	121	<i>Mer.</i>	Blaenau Festiniog ...	7·07	109
<i>Hants.</i>	St. Catherine's L'thouse	2·37	122	"	Aberdovey	4·77	194
"	Southampton, East Pk.	2·72	127	<i>Carn.</i>	Llandudno ... ..	...	...
"	South Farnborough ...	2·03	101	<i>Angl.</i>	Llanerchymedd ...	3·16	141
<i>Herts.</i>	Harpenden, Rothamsted	2·32	110	<i>I. Man</i>	Douglas, Borough Cem.	2·53	97
<i>Bucks.</i>	Slough, Upton	2·32	121	<i>Wigtown</i>	Newton Stewart ...	3·39	126
<i>Oxford</i>	Oxford, Radcliffe ...	2·05	108	<i>Dumf.</i>	Dumfries, Crichton R.I.	3·00	123
<i>N'hants.</i>	Wellingboro' Swanspool	1·93	102	"	Eskdalemuir Obsy. ...	4·60	121
<i>Essex</i>	Southend W.W.	1·75	107	<i>Roxb.</i>	Crailling... ..	1·69	109
<i>Suffolk</i>	Ipswich, Belstead Hall	1·64	92	<i>Peebles</i>	Stobo Castle	3·02	123
"	Lowestoft Sec. School	1·87	112	<i>Berwick</i>	Marchmont House ...	1·95	104
"	Bury St. Ed., Westley H.	2·12	100	<i>E. Loth.</i>	N. Berwick	1·66	114
<i>Norfolk</i>	Sandringham Ho. Gdns.	1·58	77	<i>Midl'n.</i>	Edinburgh, Blackf'd H.	1·87	115
<i>Dorset</i>	Creech Grange... ..	2·92	127	<i>Lanark</i>	Hamilton W.W., T'nhill	2·03	92
"	Beaminster, East St. ...	3·91	157	<i>Ayr</i>	Prestwick	1·70	89
<i>Devon</i>	Teignmouth, Den Gdns.	3·27	153	"	Glen Afton, Ayr San. ...	4·72	138
"	Ilfracombe	2·87	125	<i>Renfrew</i>	Greenock, Prospect Hill	4·86	137
"	Princetown	9·28	179	<i>Bute</i>	Rothsay	4·59	140
<i>Cornwall</i>	Bude	2·24	115	<i>Argyll</i>	Morven, Drimnin ...	4·42	120
"	Penzance	3·06	122	"	Ardrihaig, Canal Office	...	...
"	St. Austell	4·30	147	"	Inveraray Castle ...	6·17	121
"	Scilly, St. Marys ...	2·52	119	"	Islay, Eallabus	4·16	136
<i>Somerset</i>	Bath	2·39	113	"	Tiree	3·08	118
"	Taunton	2·54	131	<i>Kinross</i>	Loch Leven Sluice ...	2·95	137
<i>Glos.</i>	Cirencester	3·36	145	<i>Fife</i>	Leuchars Airfield ...	2·07	135
<i>Salop</i>	Church Stretton ...	4·08	159	<i>Perth</i>	Loch Dhu	6·20	126
"	Shrewsbury, Monkmore	2·92	158	"	Crieff, Strathearn Hyd.	3·30	145
<i>Worcs.</i>	Worcester, Red Hill ...	2·91	160	"	Pitlochry, Fincastle ...	3·24	171
<i>Warwick</i>	Birmingham, Edgbaston	3·88	169	<i>Angus</i>	Montrose Hospital ...	1·93	104
<i>Leics.</i>	Thornton Reservoir ...	2·70	124	<i>Aberd.</i>	Braemar	2·65	118
<i>Lincs.</i>	Cranwell Airfield ...	2·30	138	"	Dyce, Craibstone ...	3·08	140
"	Skegness, Marine Gdns.	1·61	101	"	New Deer School House	1·99	89
<i>Notts.</i>	Mansfield, Carr Bank...	3·28	166	<i>Moray</i>	Gordon Castle	1·75	96
<i>Derby</i>	Buxton, Terrace Slopes	4·13	124	<i>Inverness</i>	Loch Ness, Garthbeg ...	2·92	105
<i>Ches.</i>	Bidston Observatory ...	2·41	143	"	Fort William	6·00	126
"	Manchester, Airport ...	3·40	180	"	Skye, Duntulm... ..	4·74	139
<i>Lancs.</i>	Stonyhurst College ...	2·50	93	"	Benbecula	4·47	175
"	Squires Gate	2·72	148	<i>R. & C.</i>	Fearn, Geanies	2·46	167
<i>Yorks.</i>	Wakefield, Clarence Pk.	3·32	183	"	Inverbroom, Glackour...	5·83	137
"	Hull, Pearson Park ...	2·40	131	"	Loch Duich, Ratagan...	6·57	122
"	Felixkirk, Mt. St. John...	2·23	121	"	Achnashellach	7·43	133
"	York Museum	3·09	182	"	Stornoway	5·36	230
"	Scarborough	2·90	158	<i>Caith.</i>	Wick Airfield	1·94	96
"	Middlesbrough... ..	1·50	99	<i>Shetland</i>	Lerwick Observatory ...	3·01	111
"	Baldersdale, Hury Res.	3·00	121	<i>Ferm.</i>	Belleek	3·84	134
<i>Nor'l'd</i>	Newcastle, Leazes Pk...	1·66	95	<i>Armagh</i>	Armagh Observatory ...	2·90	140
"	Bellingham, High Green	2·71	126	<i>Down</i>	Seaforde	3·19	127
"	Lilburn Tower Gdns. ...	2·14	110	<i>Antrim</i>	Aldergrove Airfield ...	1·97	90
<i>Cumb.</i>	Geltsdale	3·00	129	"	Ballymena, Harryville...	2·78	101
"	Keswick, Derwent Island	4·53	134	<i>L'derry</i>	Garvagh, Moneydig ...	3·27	122
"	Ravenglass, The Grove	3·16	128	"	Londonderry, Creggan	4·28	143
<i>Mon.</i>	A'gavenney, Plás Derwen	4·14	145	<i>Tyrone</i>	Omagh, Edenfel	3·75	145
<i>Glam.</i>	Cardiff, Penylan	3·19	109				

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