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THE ESTIMATION OF THE DISPERSION OF WINDBORNE MATERIAL

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Introduction.—The theoretical estimation of the concentrations arising from sources of gaseous or finely divided particulate material has for long been based on treatments of atmospheric diffusion developed by Sir Graham Sutton, and subsequently expressed in the well known formulae for surface and elevated sources (see *Micrometeorology*, p. 290[1]). These formulae are reliable for specifying the average distribution, over a few hundred metres downwind of a source operating for a few minutes on level unobstructed terrain, with a steady wind direction and neutral conditions of atmospheric stability. Extension to other circumstances has depended on empirical and often speculative adjustments of the diffusion parameters.

During the last few years, further investigations at the Chemical Defence Experimental Establishment, Porton, have shown that a fairly rational allowance can now be made for the effects of much of the wide variation in atmospheric turbulence which occurs in reality. This progress includes some extension to longer distances of travel. Although many aspects of the problem require further attention, these recent developments, supported also by experimental studies in the U.S.A., form a basis for a tentative system of estimating diffusion in a wide range of meteorological conditions and over distances up to about 100 kilometres.

The purpose of this article is to review the recent background of theoretical and experimental results, and to give details of the proposed system of calculating the distribution of concentration downwind of a source. These details are set out in two appendixes, the first giving complete instructions for carrying out the calculations, the second presenting an example.

The crosswind spread of a cloud from a continuous point source.—In the earlier treatments of diffusion from a continuous point source the main feature was the adoption of a conjectured form for the Lagrangian correlation coefficient in G. I. Taylor's (1921) statistical analysis of the dispersion of particles (see *Micrometeorology*, p. 284[1]). Justification of the particular form was provided by using it to deduce a correct expression for the aerodynamic drag of a surface. In effect this meant that a correct form for the eddy diffusivity determining the vertical transport of momentum had been specified. The remaining important steps were the assumptions of identity in the diffusivities for momentum and airborne material, and of analogy in the laws governing vertical and lateral diffusion from a source in the lower atmosphere.

Taylor's analysis assumes that the field of turbulence affecting the particles is homogeneous and steady, that is, that its statistical properties do not depend on position or time. It would be difficult, if not impossible, to find any example of atmospheric turbulence in which these conditions are strictly satisfied, and indeed it is known that near the ground the structure of turbulence changes systematically with height. However, subject to certain restrictions, it is not unreasonable to assume the existence of *quasi*-homogeneous, *quasi*-steady properties in the horizontal plane, and even in the vertical plane well away from the ground. The obvious restrictions are that the structure of the flow should not be systematically patterned by dynamical or thermal influences associated with surface topography, and that its properties should not change radically over the period of interest (hence, if there is a large diurnal variation, for example, attention should be confined to small fractions of a day at a time). For such quasi-homogeneous, quasi-steady conditions a simple and direct adaptation of Taylor's treatment has been developed by Hay and Pasquill[2].

The essential step in the new treatment is the adoption of a simple hypothesis regarding the Lagrangian variations of velocity (that is, those experienced by a single particle as it travels), which are difficult if not impossible to measure, and the variations which can be observed by using an instrument at a fixed position. In terms of the auto-correlation coefficient of eddy velocity the hypothesis is that this function has the same shape (with regard to time-lag) in the two cases, but that the Lagrangian coefficient takes β times as long as the "fixed-point" coefficient to decay to a given magnitude. It can be demonstrated analytically that identity in shape is not really critical, the important requirement being that the ratio (β) of the corresponding integrals of the whole correlograms should be known. Even then it follows directly from Taylor's original treatment that the magnitude of diffusion is insensitive to β at short range, and only depends on $\beta^{\frac{1}{2}}$ at long range.

In the simple form used in practice the crosswind spread of particles from their mean position is given by

$$\sigma_y/x \simeq [\sigma_\theta]_{\tau,\, x/\bar{u}\beta} \qquad \ldots (1)$$

where σ_y is the standard deviation of the crosswind displacements of the particles at a distance x downwind, σ_θ is the standard deviation of wind direction, and $\bar{u}$ is the mean wind speed. The subscripts are used to denote that this standard deviation is obtained by forming averages of the wind direction over moving intervals $x/\bar{u}\beta$, and using the values so obtained over a duration τ, equal to the duration of release of the material, or to the duration of sampling (or exposure to) the cloud, whichever is the shorter. When $x/\bar{u}$ is greater than the duration of release (that is, when the plume is detached from the source), or than the duration of sampling of a continuous plume, the diffusion will be determined in a complex way by larger and larger eddies than those which contribute to the variation of wind direction over the time τ, and equation (1) will then underestimate σ_y.

From measurements of the crosswind spread of particles at a distance of 100 metres from a source of duration three minutes [$\tau = 3$ min in equation (1)], values of β were deduced which varied considerably but averaged about four. It was also shown that this value provided a satisfactory interpretation of diffusion data obtained earlier at Porton, and more recently in the U.S.A., for distances of travel up to about 1000 metres. Many more determinations of the effective value of β will be required to give a reasonably complete description, but for many practical purposes it would appear that a useful range of conditions is adequately represented by the foregoing value.

For ranges of travel much longer than 1000 metres the method is open to question on the grounds that as the plume spreads vertically its lateral spread will be affected by the systematic variation of wind direction with height above the ground. However, a limited examination (three cases) of the crosswind spread at a distance of about 75 kilometres showed that equation (1) did in fact give a reasonable approximation in terms of the surface wind. These cases were in daytime, with fairly vigorous mixing over a depth of about 1000 metres. The values of σ_y/x and σ_θ were as follows, the latter being determined from a Baxendall wind-direction recorder at the site of release:

σ_y/x	0·073	0·077	0·061
$[\sigma_\theta]_{\tau,\, x/4\bar{u}}$	0·084	0·066	0·068 radians.

Vertical diffusion at short range from a source at ground level.—A general treatment of vertical diffusion in the lowest layers of the atmosphere, based on laboratory laws relating wind profile and surface drag, has been given by Calder.[3] The full exploitation of the treatment requires careful specification of the vertical profile of mean wind velocity characteristic of the surface. For practical purposes, however, changes in the small-scale roughness (for example, in grass length) have only a minor effect on diffusion. For example (see Calder's paper, p. 166[3]), a six-fold increase in the roughness parameter, corresponding to a doubling of the aerodynamic drag, produces only a 25 per cent increase in the *height* of cloud at 100 metres from a source (defined here as the height at which the concentration in the cloud is one-tenth of the ground-level value). So although the treatment has only been verified for grassland, the implication is that increases in roughness of a moderate order (for example, due to crops, small bushes and hedges) are unlikely to make a vast difference to the vertical diffusion. This suggests that for open country, but away from larger disturbances such as those caused by woods, buildings or sharp changes in contour, an acceptable working approximation is probably best represented by the long-grass case (see Calder's paper, p. 166[3]), for which the heights of cloud at 100 and 1000 metres downwind are respectively 10 and 70 metres.

It should be emphasized that these figures apply only to neutral conditions of stability, and cannot be directly extrapolated to longer ranges. The latter restriction arises from the assumption in the theoretical argument that the horizontal shearing stress is constant with height. In the present state of knowledge this can be assumed with confidence only over the first few tens of metres.

The method has been extended to non-neutral conditions by Deacon,[4] using an empirical power-law form of wind profile which reduces to the required logarithmic form in the special case of neutral conditions. There is evidence for reasonable agreement with observations of diffusion in unstable conditions, though the accuracy required in measuring the wind profile is even greater than in neutral conditions and there are other difficulties when the roughness elements are easily bent over or distorted by the wind. In stable conditions the method gives discrepant results, and Deacon[5] has recently argued that this may be because of the flow not being aerodynamically rough at the very low wind speeds which then occur very close to the ground. More recently, treatments by Monin[6] have attracted much attention from an analytical point of view, but have yet to be adapted for practical use.

At the present stage the most useful guide to the estimation of vertical spread in non-neutral conditions is provided by the *Prairie Grass* measurements in the U.S.A., which have been summarized in a convenient form by Cramer.[7] These results show that *cloud height* at 100 metres downwind of the source ranged from about 4 metres in "extreme stability" to about 25 metres in "extreme instability", with 7½ metres in neutral conditions. As the site was relatively smooth (roughness parameter $z_0 < 1$ cm) the latter figure compares satisfactorily with the value of 8·1 calculated by Calder (*loc. cit.*) for a z_0 of 0·5 centimetres. The magnitudes of vertical spread at greater distances (up to 800 metres) were inferred by Cramer from the measured variations (with distance) of peak concentration and cloud width. In unstable conditions they show an acceleration of the vertical spread with increasing distance. For example, in "extreme instability" the inferred cloud height at 800 metres downwind is about 1000 metres. Because of the indirect derivation (including the assumption of Gaussian shape in the vertical distibution) it is difficult to judge the precision of this latter value. However, such a rate of spread merely requires the incidence of sustained upcurrents with an inclination of about 45°, and there is little doubt that such upcurrents do occur with light winds and well developed convection.

The effect of an elevation of the source.—When material is released at an elevated position it may be expected that the effects of the variation of wind structure with height will initially be of secondary importance. As a first approximation, therefore, the vertical spread at short range may be derived on the assumption of quasi-homogeneous turbulence. In this case, on the same lines as those followed for lateral spread, the standard deviation of vertical spread (σ_z) at distance x is given by

$$\sigma_z/x \simeq [\sigma_\phi]_{\tau,\, T/\beta} \qquad \ldots (2)$$

where σ_ϕ is the standard deviation of the wind inclination (in radians). The latter is obtained from data averaged over periods T/β ($T=x/\bar{u}$), and observed over a period τ equal to the duration of release (or of sampling) of the material. The application of equation (2) has recently been tested against experimental data obtained in the U.S.A.

Following custom, the plume from an elevated source is assumed to have Gaussian distributions of material both laterally and vertically, with standard deviations σ_y and σ_z. For simplicity, wind velocity is taken to be constant with height, and it is assumed that the effect of the ground can be represented by an *image* source (as in *Micrometeorology*, pp. 139 and 292[1]). With the usual co-ordinate system (x alongwind, y crosswind, z vertical) the continuity condition leads to the following expression for the distribution of concentration χ (x, y, z) from a continuous source of strength Q at position (0, 0, H).

$$\chi\,(x,y,z) = \frac{Q \exp\,(-y^2/2\sigma_y^2)}{2\,\pi\,\sigma_y\,\sigma_z\,\bar{u}} \left[\exp\left\{-\frac{(z-H)^2}{2\sigma_z^2}\right\} + \exp\left\{-\frac{(z+H)^2}{2\sigma_z^2}\right\}\right]. \qquad (3)$$

With the simplifying assumption that σ_y/σ_z is a constant independent of distance, differentiation of the above expression with respect to σ_z leads to the condition that χ $(x, 0, 0)$ (that is, the concentration on the axis of the plume at ground level) is a maximum when

$$\sigma_z \sqrt{2} = H. \qquad \ldots (4)$$

Similarly, if the integral of the crosswind distribution, that is $\int_{-\infty}^{+\infty} \chi\ (x, y, o)dy$, is considered, the condition for this quantity to be a maximum is

$$\sigma_z = H. \qquad \ldots (5)$$

Measurements have recently been made at the National Reactor Testing Establishment, Idaho Falls, U.S.A., of the ground-level distribution of a fluorescent tracer released at a height of about 50 metres. These provided *observed* estimates of the distance, d (max), at which the crosswind integrated concentration was a maximum. Records were also taken of the fluctuating inclination of the wind near the point of release, from which it was possible to evaluate σ_ϕ, for specified values of τ and $x/\bar{u}\beta$ as required by equation (2). Substituting the condition (5) in equation (2) gives

$$H = d\,(\text{max})\ [\sigma_\phi]_{\tau,\, s} \qquad \ldots (6)$$

with $s = d$ (max)$/\bar{u}\beta$, from which *calculated* estimates of d (max) were obtained (assuming $\beta=4$), the *observed* estimates being used in assigning the appropriate averaging time for analysing the wind trace. The observed and calculated estimates from thirteen tests are listed in Table I.

TABLE I—OBSERVED AND CALCULATED ESTIMATES OF THE DISTANCE d(max) AT WHICH THE CROSSWIND INTEGRATED CONCENTRATION AT GROUND LEVEL IS A MAXIMUM

Data obtained at Idaho Falls, U.S.A., with a source at a height of 50 metres.

Test	Observed d (max)	Calculated d (max) in metres
3	300	370
5	500	910
6	1000	850
7	600	487
8	500	445
9	600	830
11	400	305
12	600	805
13	600	790
14	400	540
15	300	370
16	700	765
17	400	304

The ratios of the calculated and observed values range from 0·76 to 1·82; apart from test 5 the range is 0·76 to 1·38; the overall average ratio is 1·14. These data suggest that useful estimates of d(max) may be made in a simple way from practicable measurements of wind fluctuations near the site of release.

Vertical diffusion at longer range.—The discussion of vertical diffusion has so far been restricted to distances of travel of about 1000 metres. For longer distances not only has there been no established treatment available, but until quite recently there were virtually no useful observational data. Consequently, estimates of diffusion at longer range have tended to be based on extrapolation of the short-range data, a somewhat dubious procedure bearing in mind the primitive state of knowledge of turbulent and convective transport processes above the immediate surface layer.

In the last few years tracer studies of diffusion over distances of tens of miles have been undertaken at Porton and elsewhere. The work at Porton has been partly concerned with horizontal spread, but the main interest has been to obtain some reliable description of the extent of vertical diffusion. Earlier stages of this work at Porton were dependent on a limited effort in sampling from aircraft, and this proved incapable of providing more than a very rough indication of the vertical distribution of the tracer material.

More recently a technique has been developed for sampling the cloud from a crosswind line-source of tracer material, using units mounted on a barrage-balloon cable, and this has given valuable preliminary data on vertical distribution at a distance of about 50 miles from a source. These data include a demonstration of relatively uniform concentration (with height) in a convective régime, with a relative sharp fall-off near the base of the overhead inversion (at about 3500 feet in the case studied). It was also found that in the absence of convection, but without any marked stabilization near the surface, vertical diffusion could be very slow. Two separate experiments showed the cloud to be essentially confined to the first 2000 feet above ground, and in one of these the material was actually released at about 1000 feet. This slow vertical spread is all the more noteworthy when it is realized that extrapolation from short-range data would lead to a cloud height of 11,000 feet. On the other hand, it is at any rate qualitatively consistent with the small vertical gustiness measured at the same time in the first few thousand feet.

The latter measurements, with others made at intermediate distances, have been shown by Hay and Smith[8] to be consistent with a new statistical treatment of the spread of a *cluster* of particles (as distinct from a continuous plume). This treatment enables approximate estimates of the spread to be made, given merely the total intensity of turbulence (in effect the σ_ϕ of equation (2) for large values of τ), though for more detailed analysis a knowledge of the energy spectrum of the turbulence is required.

A practical system for estimating the concentration or dosage pattern up to about 100 kilometres from a source (**see Appendix I**).—The method set out in detail in Appendix I is an attempt to combine in the most flexible manner the various ideas and observations which are now available. The basic assumption is that the crosswind and vertical distribution in a plume or cloud of windborne material can be represented by the Gaussian form, as adopted in equation (3). This equation implies that the wind direction is steady over the duration of release or of sampling. For general application, including highly variable wind direction, it is more convenient to use a lateral distribution on an arc centred on the source (instead of a crosswind line). Assuming this arc distribution to be Gaussian, equation (7) in Appendix I follows directly from the continuity condition.

Equation (7) gives the axial concentration from a ground-level source in terms of a lateral (angular) spread θ and a vertical spread h, which are defined by concentrations one-tenth of the axial or ground values respectively. Remembering that for a Gaussian distribution these dimensions are respectively 4·3 and 2·15 times the root-mean-square deviations from the axis or ground, it is easily verified that equations (3) and (7) are identical when θ is small, and z and H are set equal to zero.

The advantages of equation (7) are firstly its simplicity, and secondly its use of plume dimensions θ and h which can be directly envisaged. There is accordingly less likelihood of unrealistic magnitudes of θ and h being adopted. When the necessary special data on wind fluctuation are available, θ should be calculated from equation (1). Likewise, it is recommended that h be calculated from equation (2), using data on the fluctuation of wind inclination well clear of the ground, except for short distances (say < 1 km) from a ground-level source. For use in the latter circumstances, and also generally when data on wind fluctuation are not available, estimates of h and θ in broad meteorological conditions are given in Figure 2 (Appendix I).

The estimates of h in Figure 2 have the following origins:

(i) Neutral conditions (D) and distance < 1 km—experimental data consolidated by Calder's semi-theoretical treatment.

(ii) Non-neutral conditions and distance < 1 km—experimental data obtained in *Project Prairie Grass* in the U.S.A. For extremely unstable conditions a round figure of 1000 metres is adopted for h at a distance of one kilometre.

(iii) For neutral–moderately unstable conditions (D, C, B) and distance > 1 km—calculations from the available statistics on vertical gustiness,[9] supported by some experimental data.

(iv) Stable conditions (E and F) and distance > 1 km—these are essentially speculative extrapolations from the more reliable data.

The estimates of θ tabulated on Figure 2 are for a *short* release (a few minutes) and are based on recently acquired statistics of wind direction fluctuation.[10] Those for $d = 0 \cdot 1$ kilometre are derived from equation (1), while those for $d = 100$ kilometres are extremely tentative values based on a little experimental data, and on Hay and Smith's[8] treatment of an expanding cluster.

Greater uncertainty in the data of Figure 2 is implied by the thinner and broken lines for h and the addition of brackets to the figures for θ. For longer releases no attempt is made to give statistical estimates of θ, and for use in the absence of detailed measurements of wind fluctuation a rough rule is given for deriving θ from a routine wind-direction trace (see Appendix I, para. 11).

It will be noted that in the extension to an elevated source no attempt is made to adjust the values of vertical spread, h, (though this would be automatically introduced to some extent if h were calculated from equation (2) using measurements of wind inclination near the height of the source). This use of common values of h, irrespective of the height H of the source, may introduce additional error at short distances (or more strictly while h is small, and less than H say). At the present stage, however, there is insufficient data on which to base any general correction of practical consequence. It should also be emphasized that the estimates of θ and h are appropriate to fairly level open country. In an urban area, or on an industrial site, there will be additional dynamical turbulence generated by the buildings, and this may be expected to increase the spread of the plume. No quantitative data are available, but *a priori* there would appear to be no reason to expect an important effect except at relatively short distances from the source, before the spread of the cloud becomes large compared with the individual buildings. At these short distances buildings will also bring the further complication of *downdraught* and *downwash* effects, of the type described by Hawkins and Nonhebel,[11] both of which tend to bring effluent to ground level more quickly than in unobstructed flow.

The rest of the process of evaluating the distribution of concentration is dealt with in a self-contained fashion in Appendix I. It should be noted that no attempt is made to allow for deposition, decay or decomposition of the material.

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Appendix I

Instructions for the estimation of the distribution of concentration or dosage downwind of a source of windborne material

The Plume model and the formula for concentration or dosage from a ground-level source

1. Consider a ground-level source producing a plume with an idealized distribution as represented in Figure 1. Let the lateral spread θ ($=\angle$AOB) along an arc be defined by concentrations one-tenth of the peak or axial value. Similarly, let the vertical spread h be defined by a concentration one-tenth of the ground value. With the simplifying assumptions that the wind speed u is constant with height, that the material crosses the arc normally and that the crosswind and vertical distributions are of Gaussian form, the concentration distribution is completely determined by equating the rate at which material crosses the arc to the rate of release at the source.

2. For a rate of release of one "unit"/min the axial or peak concentration C_0 at ground level at distance d downwind is

$$C_0 = \frac{2 \cdot 8 \times 10^{-3}}{u\, d\, \theta\, h} \text{ "units"/m}^3, \qquad \ldots (7)$$

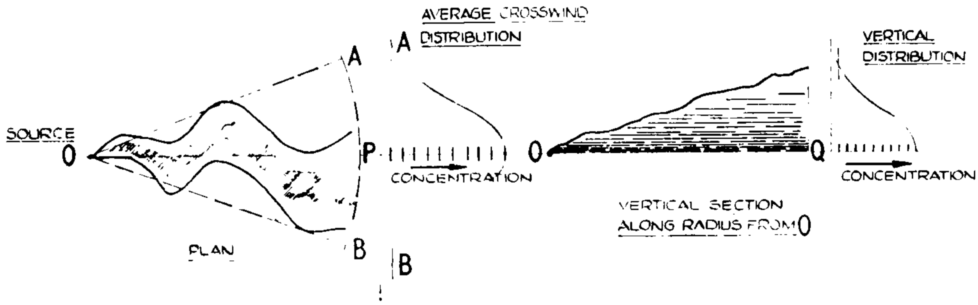


FIGURE I—SCHEMATIC DIAGRAM OF A PLUME FROM A SOURCE AT GROUND LEVEL

with u in m/sec, d in km, θ in degrees and h in metres. This is also the *total dosage* in "units" min/m^3 which would be experienced at the same position during the entire passage of the plume, when the *total* release is one unit. For any other rate of release, or total release, the values of C_0 should merely be increased in direct proportion.

3. The formula is valid in terms of concentration and rate of release provided the duration of release is sufficient for alongwind diffusion to be neglected, and in practice this may be taken to be the case when the duration of release is, say, equal to or greater than the time of travel from the source O to the point of interest P. Apart from a relatively short period near the beginning and the end, the concentration C_0 may then be regarded as obtaining (on average) for a period equal to the duration of release. On the other hand, when the release is terminated before the leading edge of the plume reaches the arc through P, the period of quasi-steady C_0 will be substantially less than the duration of release, and will be virtually nil when the duration of release is only a small fraction of the time of travel to P. In these cases, although equation (7) will give an over-estimate of the concentration experienced at P, it will still give the correct value of the *total dosage* for a *total* release of one unit.

4. On either side of P, and vertically above any point on arc AB, the concentration will fall off according to the (assumed) Gaussian form, and the complete downwind distribution may thus be determined from four parameters: the speed of the wind u (appropriately defined), the appropriate effective wind direction (fixing the position P), the vertical spread h and the lateral spread θ. The wind values need to be based on surface and upper air data, in a way which is explained later.

The estimation of the vertical spread h

5. The magnitude of h initially increases with distance d from the source, at a rate which depends on the amount of vertical mixing. If, as frequently happens, vertical transport is suppressed at some level in the atmosphere by an isothermal or inversion layer, the ultimate effect of this should be to transform the concentration profile into a uniform distribution between ground and inversion (or isothermal) base. Beyond this stage the effective value of h will be constant.

6. When data are available (either from current measurements or from

accumulated statistics) on the fluctuation of the wind inclination, values of h should be calculated from the appropriate form of equation (2), that is

$$h = 2150\, d\, \sigma_\phi \text{ metres,} \qquad \ldots (8)$$

where σ_ϕ is the standard deviation of the wind inclination ϕ (radians), obtained from averages of ϕ taken over periods equal to approximately one-quarter of the time of travel and observed for the duration of release or sampling. This procedure is recommended especially for an elevated source (for which condition corrections to equation (7) are made in para. 14), and also for a ground-level source once vertical spread has extended above the surface layer (10 metres or so in depth) in which wind shear is most pronounced.

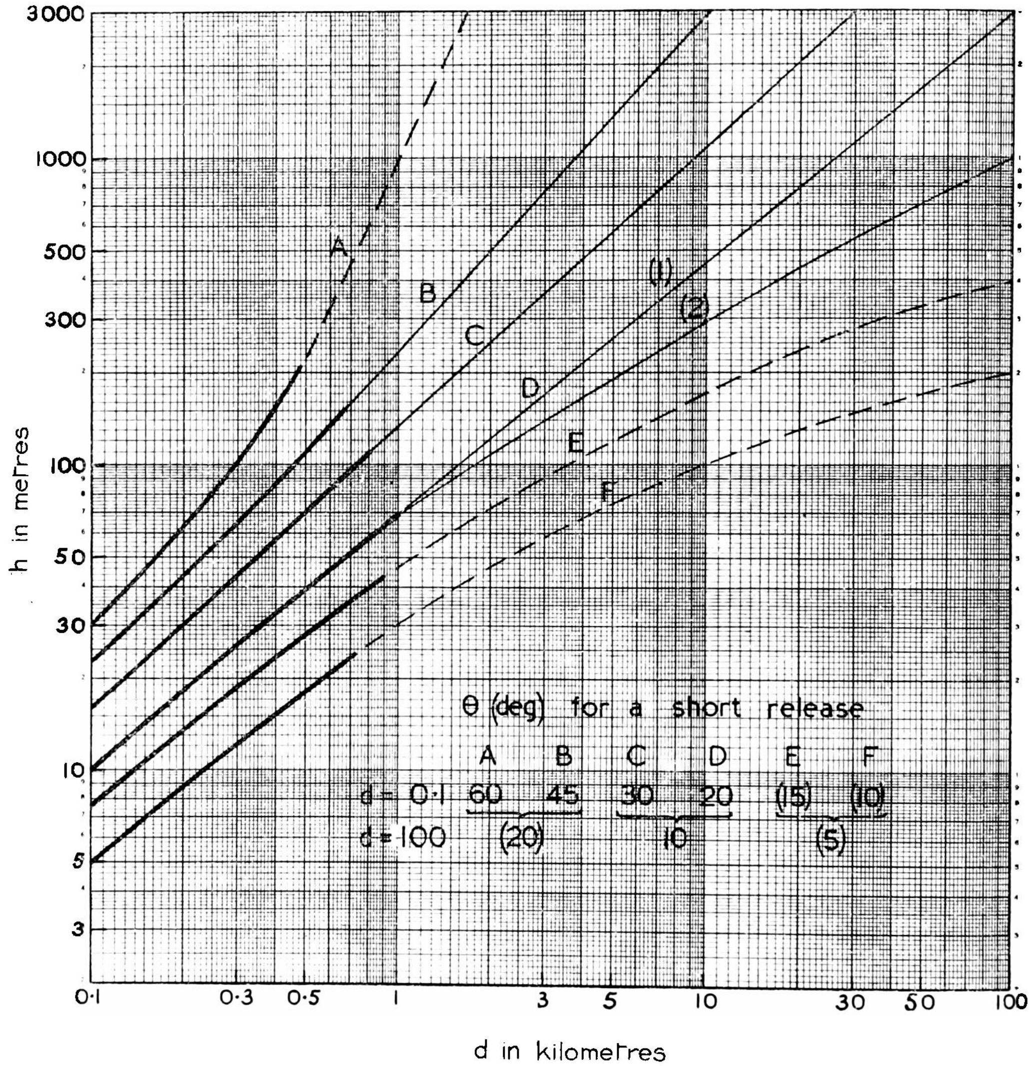


FIGURE 2—TENTATIVE ESTIMATES OF VERTICAL (h) AND LATERAL (θ) SPREAD

7. For use in the absence of wind fluctuation data, tentative estimates of vertical spread in open country are given in Figure 2 for six categories of stability (in the surface layer) which are specified qualitatively in terms of wind speed, insolation and state of sky. "Strong" insolation corresponds to sunny midday conditions in midsummer in England and "slight" insolation to

similar conditions in midwinter. Night refers to the period from one hour before sunset to one hour after dawn. The neutral category D should also be assumed, irrespective of wind speed, for overcast conditions during day or night, and for any sky conditions during the hour preceding or following night as defined above. The D(1) curve should be followed to the top of the dry adiabatic layer; thereafter, in sub-adiabatic conditions, D(2) or a curve parallel to D(2) should be followed.

TABLE II—KEY TO STABILITY CATEGORIES

Surface wind speed (at 10 m)	Insolation			Night	
	Strong	Moderate	Slight	Thinly overcast or $\geqslant 4/8$ low cloud	$\leqslant 3/8$ cloud
m/sec					
<2	A	A–B	B	—	—
2–3	A–B	B	C	E	F
3–5	B	B–C	C	D	E
5–6	C	C–D	D	D	D
>6	C	D	D	D	D

For A–B take average of figures for A and B, etc.

8. In very light winds (<2 m/sec) on a clear night, that is, conditions productive of sharp ground frost or heavy dew, the vertical spread may be even less than the values given for category F. However, because of lack of quantitative knowledge of this and because in practice the surface plume is unlikely to have any definable travel, no estimates are attempted for this case.

9. In unstable conditions the value of h estimated as in paragraph 6 or 7 should be used with increasing distance only until a magnitude h_1 is reached, equal to the estimated vertical limit of convection, at distance, say, d_1. For approximate evaluation, at distances equal to or greater than about $2d_1$, a *constant* value of $2h_1$ should be used. In calculating C_0 from equation (7) this allows roughly for the assumed development of the vertical distribution, from the Gaussian form at d_1 to uniformity at $2d_1$. (Exact allowance for a uniform vertical distribution over depth h_1 actually requires $h = 1 \cdot 71\ h_1$ in equation(7).)

The estimation of the lateral spread

10. When suitable data are available on the fluctuation of wind direction, the lateral spread should be calculated from equation (1). The θ of equation (7) is equal to 4·3 times the σ_θ of equation (1), when consistent units are used, the numerical factor being appropriate to the assumption of Gaussian distribution.

11. When fine-structure data are not available, rough estimates of θ for a long release, in the region of one hour or more, may be made from a routine wind-direction trace as follows:

$d = 0 \cdot 1$ km, difference between extreme maximum and minimum of trace over period of release,

$d = 100$ km, difference between maximum and minimum "15-minute averages" of wind direction.

For a short release (a few minutes) estimates are given on Figure 2 for the six stability categories.

The evaluation of the axial concentration

12. The axial concentration C_0 for unit source strength may be calculated forthwith from equation (7) by substituting the distance d, the estimated values of h and θ and the appropriate value of wind speed u. For most practical purposes it will be sufficient initially to do the calculation for four standard distances, 0·1, 1, 10, and 100 km. Moreover, since θ usually changes only slowly with distance, it will be adequate to take values at 0·1 and 100 km, and to interpolate for 1 and 10 km by assuming equal changes in θ in three intervals of distance. For the wind speed u the "surface" values should be used with d=0·1 and 1 km, but at the longer distances a mean value throughout the vertical extent of the plume is required. In practice, for vertical spread from a few hundred to say 1500 metres, a speed midway between the surface and geostrophic speeds should be a reasonable working approximation.

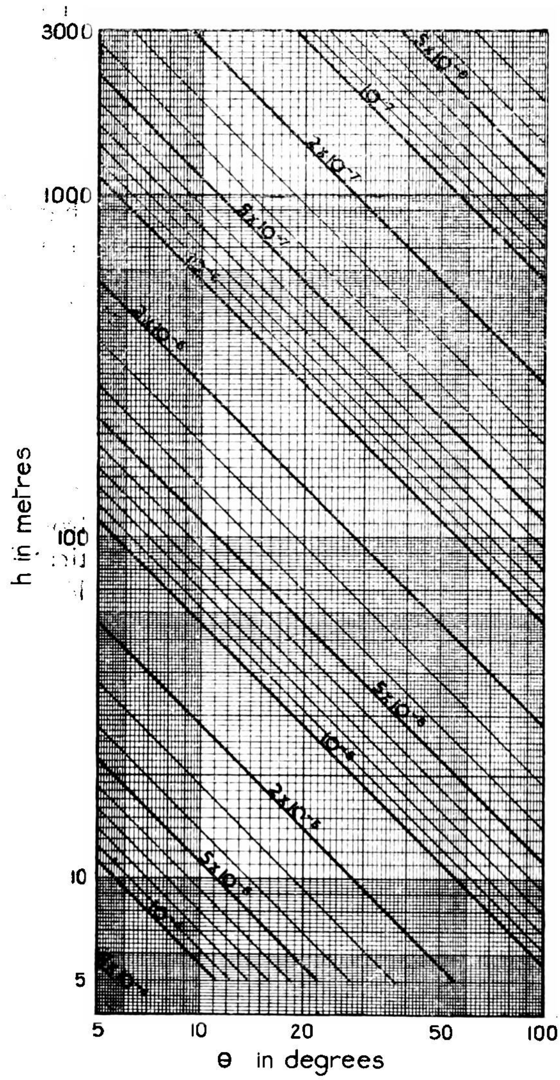


FIGURE 3—STANDARD VALUES OF AXIAL CONCENTRATION C_0 FOR d=0·1 KM AND u=5 M/SEC

For other values of d and u multiply by 0·1/d and 5/u (see equation (7)).

13. Rapid determination of C_0 may be carried out from Figure 3, which shows isopleths of C_0 for d=0·1 km and u=5 m/sec, for a practical range of h and θ. Corrections for distance and wind speed are easily made by multiplying the values from Figure 3 by 0·1/d and by 5/u. The values for the four standard distances may then be plotted on log/log graph paper for subsequent interpolation (Figure 4 shows such a graph for the example set out in Appendix 2). If the distance $2d_1$ (see para. 9) falls between 1 and 10 km, the line joining the points at 10 and 100 km should be produced backwards to $2d_1$, and the interpolated point so formed should be joined to the point at 1 km. If $2d_1$ falls between 10 and 100 km, the line joining the points at 1 and 10 km should be produced forward to $2d_1$, and the interpolated point so formed joined to the point at 100 km. (in the example in Appendix 2, $2d_1$ is 11 km but the difference between this and 10 km is disregarded, and the points at the standard distances are joined directly.)

Allowance for elevation of source

14. If the source is elevated the concentration at ground level will be reduced at the shorter distances but will tend more closely to the ground-source values as distance is increased, that is, as the cloud spreads vertically the initial effect of placing the source above the ground is progressively lost. Correction factors F_1 as a function of h/H,* where H is the height of the source, are given in the table below, and these should be used to multiply the previously derived values of C_0. For this purpose it will be necessary to take values of h at shorter intervals and this of course can be done using Figure 2. The quickest procedure is to evaluate the distances corresponding to the given values of h/H, and to apply the factors F_1 to the corresponding values of C_0 on the graph of axial concentration (see Figure 4).

h/H	1/2	2/3	4/5	1	1¼	1½	2	4	10
F_1	10^{-4}	$5\cdot6\times10^{-3}$	0·027	0·10	0·23	0·36	0·56	0·87	0·98

15. In the special conditions referred to in paragraph 8 it is possible that at the height of an elevated source the wind speed may be sufficient to give appreciable travel of the plume, though vertical spread would be negligible. This would mean that the development of vertical spread should be started not at the source, but at a downwind position corresponding to the wind speed and the estimated time for breakdown of the stable situation.

Plotting of the position and concentration of the plume (see Figure 5 for example)

16. In practice, interest will centre on the area covered by a concentration greater than some specified value. From the equivalent threshold value of concentration (that is, the actual threshold concentration divided by the source strength), the range of distance to be considered will be immediately evident. A drawing of the position and average distribution of the plume may then be prepared, as described below. If there is interest in the maximum distance of 100 km, then it will clearly not be practicable to construct the details within the 1 km distance, and for this a separate larger-scale drawing should be prepared.

* From equation (3), $F_1 = \exp(-H^2/2\,\sigma_z^2) = \exp(-2\cdot303H^2/h^2)$.

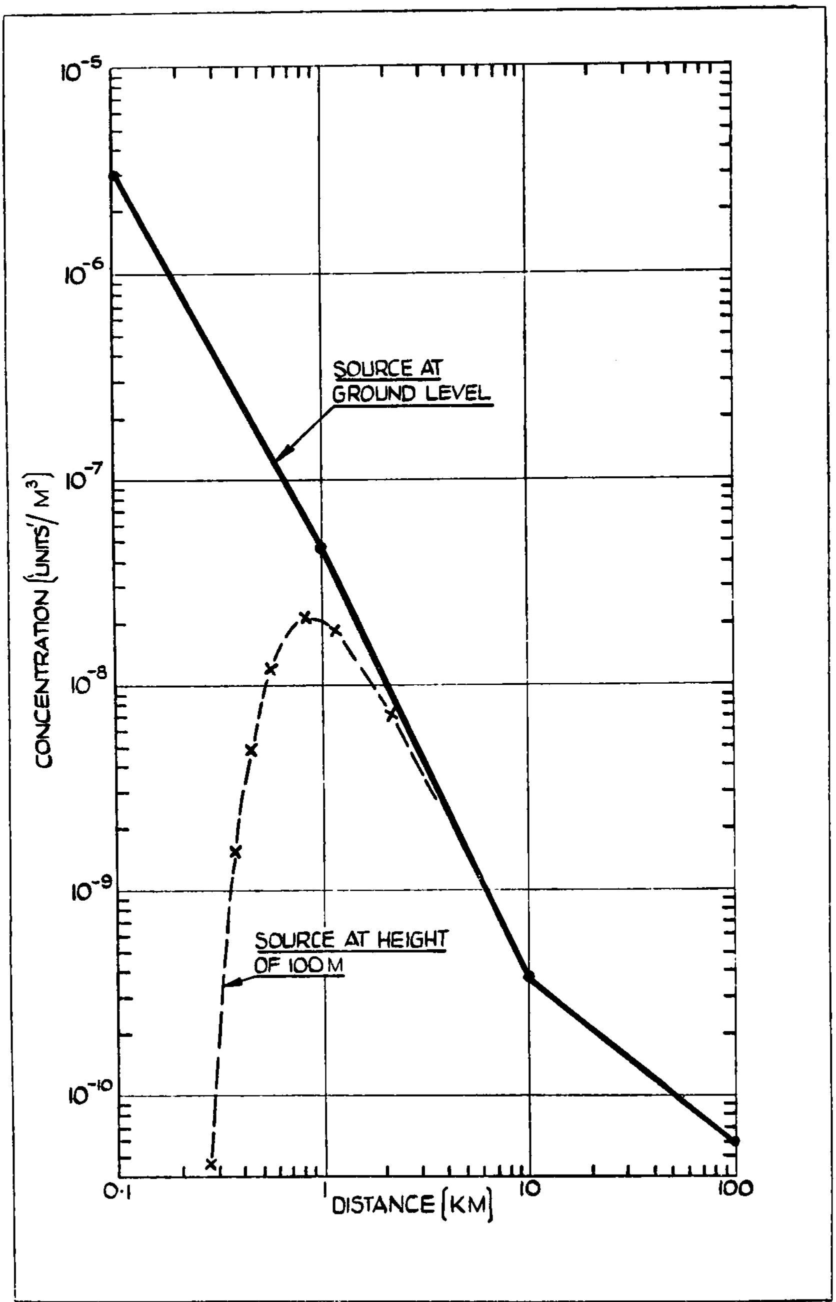


FIGURE 4—CONCENTRATION–DISTANCE DIAGRAM FOR THE EXAMPLE IN APPENDIX 2

17. The first step is to estimate the axial positions P at the various distances and these are given by effective mean wind directions as follows:

d in km	*Effective wind direction*
0·1–1	surface wind direction
10–100	average of the surface and geostrophic directions, backed by 10°

For a long release the basic estimates of wind direction should be made for the total period of release, and if direction changes with distance downwind appropriate allowance should be attempted from the synoptic data. Even in the case of a short release the important factor is the trajectory over some distance, and this will again be best given by an average wind direction corrected as necessary for variations downwind. Strictly speaking, the effective wind direction should be a mean through the vertical spread of the plume, weighted according to concentration. The rule given above for $d = 10$ to 100 km is probably adequate for h of the order 1000 m, but for very much smaller or larger values increased weight should be given to the surface or upper winds.

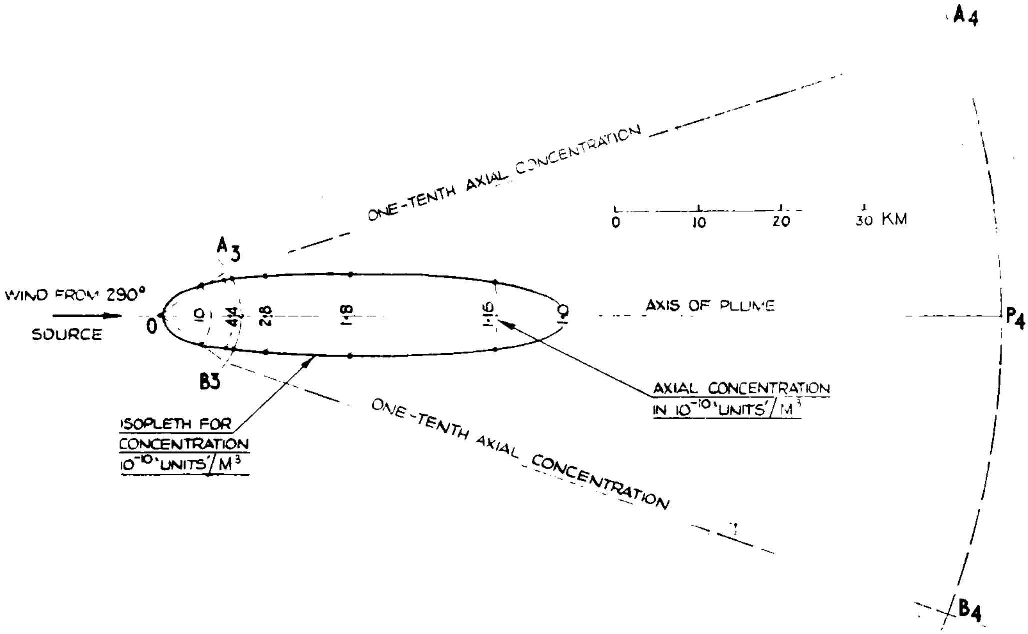


FIGURE 5—PLAN OF PLUME FOR THE EXAMPLE IN APPENDIX 2

18. Having marked the position O of the source, draw arcs at two or more standard radii (0·1, 1, 10 or 100 km). From O draw lines downwind, corresponding to the effective wind directions, to cut the appropriate arcs (at P_1 P_2 P_3 or P_4 respectively). The average plume axis is then given by joining OP_1 P_2 P_3 P_4 and values of concentration C_0 can be entered on this as required, using figures interpolated from the graph of C_0 against d. On each arc mark off points A_1 B_1 etc. symmetrically about P_1 etc., so that the angle A_1 OB_1 is equal to the estimated lateral spread θ. Then OA_1 A_2 A_3 A_4 and OB_1 B_2 B_3 B_4 are the "boundaries" of the plume, at which the concentration falls to 1/10 of the corresponding value on the axis OP_1 P_2 P_3 P_4.

19. For positions other than on the axis or "boundaries" concentrations may be interpolated by applying the following factors F_2,* which are the ratios of

* From equation (3), $F_2 = \exp(y^2/2\sigma_y^2) = \exp(2 \cdot 303(2\alpha)^2/\theta^2)$

the axial concentration to the off-axis concentration, for deviation α from the axis. These factors enable the isopleth of a given concentration to be drawn in quickly, as follows. If the given concentration is C', read off the concentration–distance graph (Figure 4) the distances at which the *axial* concentration is F_2C', and plot F_2C' on the axis of the distribution (Figure 5). Points on the isopleth of C' are then obtained by marking off the corresponding deviations α from the axis.

Deviation α from axis (fraction of $\theta/2$)	0	$\frac{1}{4}$	$\frac{1}{2}$	2/3	4/5	1	$1\frac{1}{4}$	$1\frac{1}{2}$	2
$F_2 = \frac{\text{axial conc.}}{\text{off-axis conc.}}$	1·0	1·15	1·8	2·8	4·4	10	37	180	10^4

Allowance for type of wind direction variation

20. The above procedure is based on a Gaussian distribution of the fluctuating wind direction, and this can be assumed to apply sufficiently well as long as the *fluctuations* are large compared with any discernible systematic trend over the period of release. On the other hand, if there is a systematic veering or backing of the direction, over a range large compared with the width of the trace, then the factors in paragraph 19 will not apply. The procedure should be exactly as before up to the construction of the plume position, but then the concentration should be taken as uniform along any given arc, and equal to $0{\cdot}58C_0$ ($\frac{1}{2}C_0$ will be adequate for most practical purposes), up to the cloud "boundaries" OA_1 A_2 A_3 A_4. and OB_1 B_2 B_3 B_4.

Rapid evluation of the distance and magnitude of the maximum ground-level concentration from an elevated source

21. If interest or time is insufficient for carrying out the full procedure, an estimate may quickly be made of the distance d (max) along the axis, of the maximum ground-level concentration from an elevated source. Assuming that the lateral and vertical spread have the same variation with distance (that is, that $h/\theta d$ is independent of distance), d(max) is the distance at which h is approximately 3/2 times the effective height H of the source. Having decided on the stability category, and given H, d(max) can thus be read directly from Figure 2.

22. The magnitude of this maximum concentration, that is C_0(max), for a release of one "unit"/min, is given by

$$C_0(\text{max}) \simeq \frac{2 \times 10^{-3}}{3\,u\,d(\text{max})\,\theta\,H} \text{ "units"/m}^3, \qquad \ldots (9)$$

with u, d(max) and θ in the practical units adopted in equation (7), and H (the height of source) correspondingly in metres.

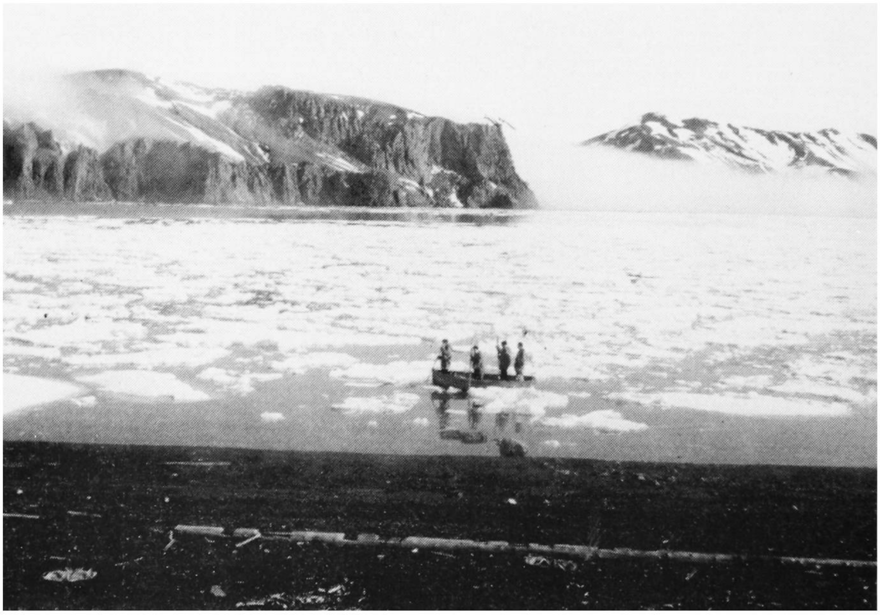
Accuracy

23. It is emphasized that the present system can in general give only very approximate estimates of the magnitudes of the concentrations, especially when it is necessary to use the tentative statistical estimates of h and θ. In the more difficult cases of unstable and stable situations, it is obvious that errors in h of several fold could be involved at the longer distances of travel, and this should be kept in mind in applying the data to the assessment of hazards. On the other hand there will be relatively straightforward cases when the estimates of vertical spread may be expected to be correct within a factor of two, namely:

[To face p. 48

Photograph by D. J. George, F.I.D.S.

PLATE I—OROGRAPHIC CUMULUS ON BRABANT ISLAND, FALKLAND ISLANDS DEPENDENCIES, MARCH 1954



Photograph by D. J. George, F.I.D.S.

PLATE II—SUMMER SEA FOG SPREADING IN THROUGH ENTRANCE TO HARBOUR AT DECEPTION ISLAND, FALKLAND ISLANDS DEPENDENCIES, JANUARY 1954

Photograph by D. J. George, F.I.D.S.

PLATE III—DRIFTING AND BLOWING SNOW AT ADMIRALTY BAY, FALKLAND ISLANDS DEPENDENCIES, MAY 1954

[*To face p. 49*

Photograph by D. J. George, F.I.D.S.

PLATE IV—HOLE IN STRATOCUMULUS, DECEPTION ISLAND, FALKLAND ISLANDS DEPENDENCIES, WINTER 1953

The cloud was formed orographically by the ridges of Deception Island. The hole was apparently produced by the freezing of a water-droplet cloud, and fibrous trails of ice crystals can be seen below the hole. There were no aircraft in the vicinity.

(i) all stabilities except extremes, for distances of travel of a few hundred metres, in open country,

(ii) neutral to moderately unstable conditions, for distances of a few kilometres,

(iii) unstable conditions in the first 1000 metres above ground, with a marked inversion thereafter, for distances of travel of 10 kilometres or more.

24. Uncertainties in the lateral spread of the plume are likely to be less important, except when the wind field is indefinite, in which case an even more important error will be that involved in prescribing the *position* of the plume. In such circumstances the best procedure would be to estimate the concentrations in the usual way, but then to allow for a wide range of possible directions of the plume, even to the extent of a full 360° in the most indefinite wind situations.

Appendix 2

Example of calculation of distribution of concentration from a point source of strength one "unit"/min

(Figures in parentheses are relevant paragraph numbers in Appendix 1.)

General data

Site ...	Southern England
Date ...	16 June 1959
Period ...	1000–1300 GMT
Effective height of release (H) ...	100 m
Surface wind ...	4 m/sec, 275°
Geostrophic wind ...	8 m/sec, 325°
Vertical extent of convection ...	1000 m
State of sky ...	1/8 Cu, 6/8 Sc, 6/8 Ci
Stability category (7) ...	B–C
Distance at which vertical spread (h), from Figure (2), equals vertical extent of convection ...	5·5 km

Calculation of C_0, equation (7)

Distance d ...	0·1	1	10	100	km
Effective value of h (7) ...	20	170	2000	2000	m
Lateral spread θ (11)* ...	120	93	67	40	deg
Effective value of u (12) ...	4	4	6	6	m/sec
C_0 ...	$2·9\times10^{-6}$	$4·4\times10^{-8}$	$3·5\times10^{-10}$	$5·8\times10^{-11}$	units/m³

Allowance for elevation of source (14)

Assumed h/H ...	1/2	2/3	4/5	1·0	1½	2·0	4·0	
$F_1 = \exp(-2·303H^2/h^2)$ ...	10^{-4}	$5·6\times10^{-3}$	0·027	0·10	0·36	0·56	0·87	
Distance at which corresponding values of h occur (Figure 2)	0·28	0·37	0·46	0·59	0·86	1·15	2·20	km
C_0 ...	4600	2700	1800	1200	580	330	82	10^{-10} units/m³
F_1C_0 ...	0·46	15	49	120	210	185	71	10^{-10} units/m³

Position of plume axis (18)

Distance ...	0·1	1	10	100	km
Effective wind direction (17) ...	275	275	290	290	deg

Rapid evaluation of d (max) and C_0 (max) (21, 22)

h at d (max) $= 3H/2 = 150$ m

$\therefore$ d (max) (from Figure 2) $= 0·85$ km

$$C_0 \text{ (max) (from equation (9))} = \frac{2\times10^{-3}}{3\times4\times0·85\times95\times100}$$

$$\simeq 2\times10^{-8} \text{ units/m}^3.$$

* Obtained from routine wind-direction trace.

551.591.3:551.555.8 (53)

DUST HAZE AT BAHRAIN

By J. HOUSEMAN

Poor visibility, caused by blowing dust and dust in suspension, is frequent over the deserts of Iraq and northern Arabia, especially during the summer months. The prevailing winds over these deserts are north-westerly. Bahrain Islands, in the Persian Gulf, lying to the south-east of the deserts, are consequently to leeward and are also affected by the dust.

The increasing use of jet aircraft with their voracious appetites for fuel makes the forecasting of landing conditions more and more important. This is especially so for aircraft scheduled to land at Bahrain as, when dust is widespread over Iraq, Arabia and the Persian Gulf, the nearest unaffected airfield may be Damascus, over 800 miles away. An investigation into dust haze conditions was undertaken in the hope that it would be of value both to forecasters and to aircraft operators for long-term flight-planning purposes.

Reduction of visibility by dust at Bahrain Airport is partly influenced by the geographical position of the airfield and partly by local topography. The airfield is situated on the northern side of Muharraq Island, which lies north of Bahrain Island and some 25 to 30 miles east of the Arabian mainland.

With only very few exceptions, dust-raising winds are of the north-westerly type, known locally as "Shamal". Consequently dust affecting the airfield is nearly always brought from the Arabian coast, or from Iraq some 250 miles to the north-west. Locally lifted dust, unmixed with Arabian dust, while often raised over the main island to the south, only affects the airfield in squally conditions such as those connected with the passage of active fronts. It is infrequent over the airfield and is usually of short duration.

In general, winds of at least 25 knots are needed to lift local dust at the airfield and winds of over 40 knots are required to give severe reductions in visibility. On the other hand, dust which has been lifted over Iraq or Arabia and is held in suspension can reduce visibility for days at a time with only very light local winds. This type of dust haze is therefore more frequent than that caused by dust raised locally and can be considered the main subject of the investigation, though it has not been possible to differentiate between the two forms as they occasionally occur in conjunction.

Method.—The method used in the investigation is similar to that which has been used by a number of others in examining the frequency of fogs. The period investigated is from 1 January 1956 to 31 December 1958. The percentage frequencies of the occurrence of various visibilities for each hour of the day throughout the period have been evaluated and some of the results are illustrated graphically in Figures 1 and 2.

The three years show considerable variation in individual dust haze patterns and this variation obviously affects the results, but random sampling over ten other years indicates that the mean figures obtained are largely representative, provided only frequencies of 10 per cent and upwards are regarded as significant. The figures refer only to occasions when visibility was reduced solely by dust. Mist and fog are not included.

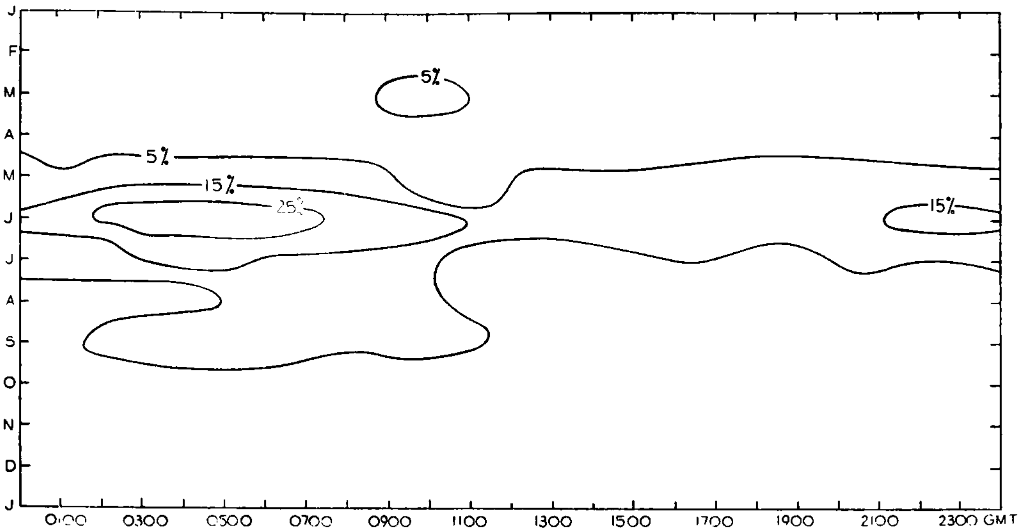


FIGURE 1—PERCENTAGE FREQUENCIES OF VISIBILITIES ⩽ 3 N. MILES

Dust haze frequency and the climatological régime.—The main point of interest emerging from the figures is the way in which the dust frequency fits the climatological régime of the area. November to February is the rainy season and, although strong winds are then more frequent than in summer and the rainfall is slight, the moistening of the desert surface is still enough almost completely to prevent dust haze. In fact, in the period December to February dust was all caused by the passage of cold fronts accompanied by thunderstorms and squalls and was a mixture of locally raised dust and dust carried along by the fronts.

During March the surface soil begins to dry out and dust haze becomes more frequent, though the percentages are still low and the actual reduction in visibility is slight. Dust is partly brought from the mainland in suspension and is partly lifted locally by strong winds giving a small increase in frequency around midday when convection and gustiness are at their maximum.

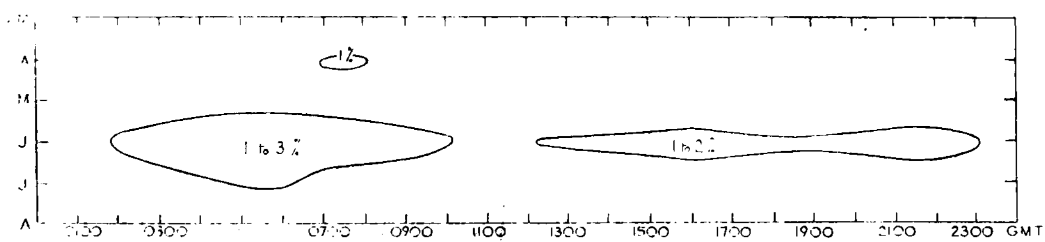


FIGURE 2—PERCENTAGE FREQUENCIES OF VISIBILITIES ⩽ 1100 YARDS

From May, through June and July the dust is at its worst. This period, especially June and the beginning of July, is the time of the "forty-day Shamal", an almost continuous north-west wind of varying strength, usually about 15 to 20 knots, associated with the monsoon low over India and Persia. It is noticeable that the highest frequency in these months occurs at 0400 GMT. This is caused by dust, picked up over Iraq during the afternoon and carried some 250 to 300 miles at 15 to 20 knots, reaching Bahrain in the early part of the following day.

This tendency for the highest frequencies to occur in the early morning continues through August to October, although August, which is usually a month of light winds, often south-easterly, shows a very much reduced total frequency. In September the winter régime of short periods of strong north-westerlies alternating with short periods of lighter winds begins again, but with the first rains over the northern desert in October the dust-raising properties of the stronger winds are much curtailed and a rapid reduction in dust frequency occurs. The more general rain of November settles almost all the dust other than that raised by the occasional front.

Occasions of very poor visibility.—Reduction of visibility below 2200 yards is most infrequent and reductions below 1100 yards are even more so. During the period examined reductions below 1100 yards occurred only in the six months March, April, May, June, July and December and only in the month of June did they last for more than two hours.

Average visibility.—Visibility in dust haze averages 3000 to 3500 yards. Once a slow improvement has brought visibility to three nautical miles, further improvement to six to ten nautical miles is usually rapid. During the winter months visibilities of 15 to 20 nautical miles are frequent.

Conclusions.—From October to February the chances of aircraft movements being hampered by dust haze at Bahrain are almost negligible. March and April remain clear for night operations and are only occasionally hazy by day. During May, June and July dust may affect the airfield at any time, the worst month being June and the worst period being around dawn with a tendency towards improvement in the late afternoon. August and September are again usually clear during the afternoon and night but are occasionally hazy in the mornings.

Even when dust is present average visibility is 3000 and 3500 yards. Reductions to below 1100 yards are only likely in June or during the passage of a squall.

551.501.45:551.501.7:681

ROUTINE COMPUTATION OF MONTHLY UPPER AIR STATISTICS USING AN ELECTRONIC COMPUTER

By D. DEWAR, B.Sc.

Introduction.—In order to make full use of the results of the daily upper air soundings carried out for synoptic purposes at radio-sonde stations controlled by the Meteorological Office, it has been the policy of the Upper Air Section of the Climatological Division to have these data entered on suitable forms each month, and to use them for the production of monthly routine statistics giving values which are likely to be required at short notice for research, investigations, or the supply of information for aviation requirements.

In the early days of the Upper Air Section the computations were carried out by assistants with the aid of adding machines and tables only. Starting with data for 1948, much of the laborious arithmetic was eliminated by the use of punched cards and Hollerith machines but a lot of computing still had to be done by assistants using desk machines, and the checking of the computations and entries of final results on summary sheets required a considerable amount of assistants' time each month. A further step forward has now been made, after some months of development work, by the use of machine "programmes" (coded instructions directing the operation of the computer) which enable nearly all the monthly routine computations to be done by the Ferranti Mercury computer installed in the Central Forecasting Office at Dunstable. A brief account of the procedure followed is given below.

Checking of data and conversion to tape procedure.—A rigorous checking system is used to try to ensure that errors in entries on the forms are eliminated before the forms are passed for the data to be punched on Hollerith cards and subsequently converted to the symbols on a reel of paper tape required for use in the computer. Errors which are not detected until the results of the machine processing are scrutinized entail an exorbitant waste of time in correcting the forms, Hollerith cards and data tapes.

All the data required for the upper wind statistics for one ascent are given on one Hollerith card. Four Hollerith cards are used to record values of temperature, heights of isobaric surfaces and humidity at standard pressure levels for one ascent, and for technical reasons it was decided that it would be best to record on the tape the data from the first Hollerith card (giving data for the lowest four pressure levels) for each day of the month, then data for the second Hollerith card (giving data for the next four pressure levels) for each day and so on. Before conversion to tape, the cards are "sequence checked" on a collator; though not infallible this check virtually ensures that all the cards in a pack are those for the required station, year, month, etc. A further check is provided by hand-punching at the beginning of each data tape a "preamble" giving the station number, year, month and hour to which the data relate; instructions in the programme provide for these particulars to be checked against those given at the beginning of each daily card and if there is disagreement the computer prints REJECT followed by information which indicates why the data were rejected. This checking procedure is considered worthwhile, although it adds to the operating time, as it also acts as a check on the correct functioning of the machines themselves.

Development of machine programmes

(*a*) *Wind programme.*—The development of the programmes was initiated by Mr. J. S. Sawyer, then Chief Forecasting Research Officer, who produced a demonstration "Autocode" programme for computing wind statistics using the daily wind components and also indicated the procedure to be followed to convert the data punched on Hollerith cards to a form, on tape, suitable for reading into the computer. Some modifications and additions have since been made to this programme to speed up the input of the data* and to provide for values for all hours combined to be given in addition to values for each hour of observation. Part of the print-out of results for Bahrain for October 1958 is shown in Table I. The programme provides for the output punch of the computer to give only essential indicative information and the required statistics; explanatory titles, numbering of columns, etc. have been added in italics in this illustration. In actual use, the results are filed in folders, one for each station, and a key to the data is provided inside each folder.

Values of the "all hours" mean components, etc. are computed by dividing totals for all hours by the total number of observations as this practice had been

* Mr. P. B. Sarson suggested this improvement and carried out the necessary amendments to the programme.

TABLE I—WINDS FOR BAHRAIN, OCTOBER 1958

	(a)	(b)	(c)	(d)							
	40427	58	10	12							
Level (mb)	(e)	(f)		(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)
850	2·5	−2·4		316	3·4	11·4	12·7	31	327	37	18
700	4·3	0·1		2	4·3	13·9	15·0	31	331	31	18
500	4·5	−15·3		286	15·9	21·1	18·7	31	277	51	15
400	5·0	−22·1		283	22·7	27·3	21·2	31	259	54	31
300	0·8	−29·3		272	29·3	34·4	25·2	31	283	69	15
200	−6·4	−33·3		259	33·9	39·0	27·5	31	247	67	10
150	−12·2	−32·9		250	35·1	38·5	27·5	29	247	86	30
100	−4·9	−13·5		250	14·4	18·1	16·0	27	277	40	14
(p)	1436	143	241	87	30						
	Combined hours data										
850	3·6	−0·5		352	3·6	12·2	13·1	45			
700	3·8	0·1		1	3·8	14·6	15·9	45			
500	4·7	−13·0		290	13·8	19·1	18·2	44			
400	5·3	−19·7		285	20·3	24·6	20·7	43			
300	0·1	−26·6		270	26·6	31·2	24·2	41			
200	−7·5	−29·9		256	30·9	35·3	26·3	40			
150	−12·6	−29·3		247	31·9	35·0	26·3	38			
100	−6·6	−12·0		241	13·7	17·6	15·7	36			

(a) Station number
(b) Last two figures of year
(c) Month
(d) Hour of observation
(e) Mean N–S components
(f) Mean E–W components
(g) Vector mean wind direction
(h) Vector mean wind speed
(i) Scalar mean wind speed
(j) Standard vector deviation
(k) No. of observations
(l) Direction of max. wind
(m) Speed of max. wind
(n) Date of max. wind
(p) Data for max. wind at any level—height (decametres), pressure, direction, speed, date

Speeds are in knots; directions are in degrees from true north.

followed in earlier years; a change to the method advocated by the Climatological Commission of the World Meteorological Organization in its *Guide to climatological practices*, whereby an "all hours" mean value is taken as the mean of the values for the separate hours, will probably be made in January 1961, the end of the current five-year climatological period.

(*b*) *Programme for temperature etc.*—This programme is more involved than the wind programme as the data for one ascent are recorded on four Hollerith cards and three elements—temperature, heights of isobaric surfaces and humidity mixing ratios—are dealt with.

Table II shows the print-out, for all levels for one hour of observation and for both hours combined, of statistics of heights of isobaric surfaces and temperatures. Column numbers in italics and a key to the values have been added but otherwise the values are as printed out from the output tape by a teleprinter.

Statistics of temperature and height are first computed for the surface,* 900, 850 and 800-millibar levels, and are then printed out and also stored for use in the "both hours" computations. This part of the programme is then repeated three times to deal with the other twelve pressure levels, four at a time. The programme contains instructions which cause the machine to print out days for which data are missing for *all* the four levels being dealt with and to add in the number of these missing days to a count which it is instructed to make of consecutive days with missing data at *any* of the levels; if there are five or more consecutive missing observations, the machine prints an asterisk for

* The height of the 1000-millibar surface is given in place of the surface height.

each such occurrence beneath the appropriate pressure-level figures. The object of this procedure is to allow a user to judge from the number of observations and the number of asterisks how much reliance he can place on values for that pressure level. At 50 millibars in Table II, for example, there were eleven observations and these, if there was no gap of five days or more, could just be regarded as giving a satisfactory mean value. The asterisks, however, indicate that there were two such gaps. It was not considered practicable to provide for this indication of reliability to be given for the "both hours" values also.

The next part of the programme provides for the computation of similar values for both hours combined and for the differences between the 12 h and 00 h means of temperature and height to be printed. These differences, in addition to providing useful information, enable a quick rough check of the mean values to be carried out. Provision has also been made for a rough check of extreme values to be carried out by the computer; if the range of either the isobaric heights or temperatures exceeds five times the appropriate standard deviation a query is printed in the space beneath the figures giving the difference between the mean values.

TABLE II—TEMPERATURES AND HEIGHTS OF ISOBARIC SURFACES, FOR BAHRAIN, OCTOBER 1958

(a)	(b)	(c)	(d)			
40427	58	10	12			
(e)	(f)	(g)	(h)	(i)	(j)	(k)
1000	2921	983	94	31·7	135	36
	31	31	21·4	1·8	63	28
900	31886	782	1029	25·2	1061	29
	31	31	17·4	2·1	1003	21
850	47339	668	1527	21·5	1555	25
	31	31	15·4	2·2	1505	17
800	63481	539	2048	17·4	2079	20
	31	31	14·1	2·0	2029	13
700	98236	278	3169	9·0	3210	11
	31	31	13·8	1·4	3148	5
600	137172	24	4425	0·8	4466	5
	31	31	13·1	2·3	4402	−3
500	181860	−242	5866	−7·8	5906	−4
	31	31	19·3	1·9	5829	−12
400	234445	−617	7563	−19·9	7606	−17
	31	31	26·7	1·7	7509	−23
300	298630	−1085	9633	−35·0	9700	−32
	31	31	36·2	2·1	9560	−39
250	337310	−1334	10881	−43·0	10960	−2
	31	31	43·0	7·8	10790	−50
200	382620	−1693	12343	−54·6	12430	−50
	31	31	52·8	2·0	12230	−59
150	424120	−1974	14137	−65·8	14220	−61
	30	30	59·6	2·2	14030	−71
MISSING	16 — 16					
MISSING	25 — 25					
100	479380	−2197	16530	−75·8	16610	−67
	29	29	49·5	3·5	16450	−81
80	499050	−2075	17823	−74·1	17890	−64
	28	28	39·5	4·8	17720	−85
60	410190	−1375	19533	−65·5	19620	−59
	21	21	44·7	3·3	19460	−70
50	227150	−675	20650	−61·4	20700	−56
**	11	11	37·9	3·2	20580	−66

TABLE II—TEMPERATURES AND HEIGHTS OF ISOBARIC SURFACES FOR BAHRAIN, OCTOBER 1958 (*cont.*)

(*a*)	(*b*)	(*c*)	(*d*)					
40427	58	10	BOTH					
(*e*)	(*f*)	(*g*)	(*h*)	(*i*)	(*j*)	(*k*)	(*l*)	(*m*)
1000	5757	1836	93	29·6	135	36	3	4·2
	62	62	22·2	2·8	56	24		
900	63712	1583	1028	25·5	1062	29	2	−0·6
	62	62	17·7	2·5	999	20		
850	94658	1351	1527	21·8	1559	25	1	−0·5
	62	62	15·6	2·3	1503	17		
800	126988	1091	2048	17·6	2079	21	−1	−0·4
	62	62	14·3	2·2	2027	12		
700	196550	565	3170	9·1	3210	12	−3	−0·3
	62	62	13·7	1·5	3148	5		
600	274477	61	4427	1·0	4466	6	−4	−0·4
	62	62	13·2	2·4	4402	−4		
500	363911	−472	5870	−7·6	5912	−4	−6	−0·4
	62	62	20·2	2·0	5829	−12		
400	469110	−1231	7566	−19·9	7621	−15	−7	−0·1
	62	62	28·6	1·8	7509	−24		
300	597610	−2158	9639	−34·8	9720	−31	−11	−0·4
	62	62	39·5	2·3	9560	−39		
250	675000	−2691	10887	−43·4	10990	−2	−12	0·7
	62	62	47·6	5·8	10790	−50		
200	765760	−3369	12351	−54·3	12470	−50	−17	−0·5
	62	62	57·6	2·1	12220	−59		
150	863030	−3998	14148	−65·5	14270	−61	−21	−0·5
	61	61	64·9	2·1	14000	−71		
100	992620	−4549	16543	−75·8	16690	−67	−26	0·1
	60	60	56·4	3·2	16430	−81		
80	1052370	−4341	17836	−73·6	18000	−63	−26	−1·0
	59	59	50·9	4·4	17720	−85		
60	978090	−3202	19558	−64·2	19780	−55	−50	−2·5
	50	50	56·5	3·9	19460	−70		
50	703560	−2031	20682	−60·2	20940	−53	−63	−2·4
	34	34	69·2	3·6	20580	−66		

			Upper line	*Lower line*
(*a*) Station number		(*f*)	Height total	No. of obs.
(*b*) Last two figures of year		(*g*)	Temperature total	No. of obs.
(*c*) Month		(*h*)	Mean height	S.D. of height
(*d*) Hour of observation		(*i*)	Mean temperature	S.D. of temperature
(*e*) Pressure level*		(*j*)	Max. height	Min. height
		(*k*)	Max. temperature	Min. temperature

(*l*) Difference 12h–00h mean heights
(*m*) Difference 12h–00h–mean temperatures
Heights are in metres; temperatures are in °C.
* Height values are for 1000 mb, temperatures for surface.

The third part of the programme instructs the machine to compute daily values of humidity mixing ratio from the values of temperature and relative humidity (which were stored during input) and values of saturation vapour pressure which were read in as part of the programme instructions. Statistics are then computed, printed and stored for the first hour and a similar procedure followed for data for the second hour. Data for both hours combined are then computed and printed. Results for Bahrain for one hour and for both hours combined are shown in Table III. Explanatory headings have been added in italics but otherwise the Table is as printed out from the tape output.

The "both hours" mean values in this programme are obtained by taking the mean of the values for the separate hours.

TABLE III—HUMIDITY MIXING RATIOS FOR BAHRAIN, OCTOBER 1958

H.M.R. DATA

(a)	(b)	(c)	(d)			
40427	58	10	12			
(e)	(f)	(g)	(h)	(i)	(j)	
1000	490·8	31	15·83	22·7	8·4	
900	191·3	31	6·17	12·2	1·8	
850	144·6	31	4·66	6·8	1·6	
800	114·3	31	3·69	5·9	1·2	
700	79·7	31	2·57	4·2	0·7	
600	45·0	31	1·45	3·0	0·3	
500	20·9	31	0·67	1·5	0·1	
400	8·5	31	0·28	0·8	0·0	
300	2·7	31	0·09	0·3	0·0	
40427	58	10	BOTH			
						(k)
1000	1046·0	62	16·87	22·7	8·4	−2·08
900	393·6	62	6·35	12·2	1·8	−0·36
850	304·8	62	4·92	7·3	1·6	−0·50
800	238·3	62	3·84	8·1	1·2	−0·31
700	159·7	62	2·58	4·4	0·6	−0·01
600	91·2	62	1·47	3·1	0·3	−0·04
500	42·7	62	0·69	1·5	0·1	−0·03
400	17·5	62	0·28	0·8	0·0	−0·01
300	5·6	62	0·09	0·3	0·0	−0·01

(a) Station number
(b) Last two figures of year
(c) Month
(d) Hour of observation
(e) Pressure level*
(f) Total
(g) No. of obs.
(h) Mean
(i) Max. value
(j) Min. value
(k) Difference 12h–00h means

Humidity mixing ratio values are in gm kg^{-1}.

* Values given against 1000 mb are actually surface values.

Computation, output and printing-out times

(*a*) *Wind programme.*—The initial reading-in of the programme instructions takes about one minute but this, of course, has only to be done once for all stations processed during a session. Reading in the data and computing statistics for one hour of observation takes about 23 seconds and punching out the results takes about 22 seconds. For a station making four ascents a day the total machine operating time is roughly 3¼ minutes. Subsequent printing out of the data from the output tape requires 9½ minutes.

(*b*) *Programme for temperature etc.*—The initial reading-in of this programme takes just over two minutes. Reading in and computing data for heights and temperatures for one set of levels (for example, 700, 600, 500, 400 millibars) takes about 14 seconds and a further 17 seconds are required to punch out results. To compute and punch out all the humidity mixing ratio values takes a little over a minute. The total operating time for a station making two ascents a day is a little over 6¼ minutes, but printing out the data from the output tape requires about 25 minutes.

(*c*) *Total times.*—Using the above test times and making allowances both for the time required to insert tapes in the tape reader and for shorter processing times for stations not making the normal two temperature and four wind ascents a day, it is estimated that, with the present programmes, for the 24 or so stations to be dealt with each month, about four hours will be required to compute and punch out the data and about twelve hours to print out the values. It is hoped shortly to modify the programmes so as to be able to use the line printer attached to the computer. This would greatly reduce the printing-out time and an output tape would then no longer be essential; if it is decided that this output tape could be dispensed with, it should be possible to reduce the total computing and printing-out time to something of the order of three hours.

It is not possible, for several reasons, to give a satisfactory answer to the obvious question, how much time does the new procedure save? Firstly, the work, to some extent, is still in the experimental stage and sufficient experience has not yet been gained to make a reliable estimate of times required for the ancillary processes—preparation of data tapes, scrutiny and, if necessary, correction of results necessitated by incorrect basic values or faulty printing. Secondly, the computer does far more than could be done by the assistant staff available. One interesting comparison can however be given. Some years ago similar wind statistics to those obtained from the computer were worked up by assistants from Hollerith tabulations, though only for "all hours combined". The production of the required Hollerith tabulations took more time than is now required for the conversion of the cards to tape for use by the computer. The computation and checking of statistics worked from the Hollerith tabulations for the 20 or so stations then dealt with took a time equivalent to that of one assistant's work for about 15 days. Using the computer, a reasonable time per station for computing and punching out results for "both hours combined" is about 130 seconds and for printing out results a little under two minutes is required, that is, about $1\frac{1}{2}$ hours for 24 stations.

The best answer probably is that the new procedure permits many more data to be computed using fewer staff for this side of the work and, what is perhaps more important still, it substitutes intelligent scrutiny by the assistants for the repetitive numerical drudgery they were formerly required to carry out.

REVIEWS

Atlantic hurricanes, by G. E. Dunn and B. I. Miller 9in. × 6in., pp. xx+326, *illus.*, Interscience Publishers Inc., 250 Fifth Avenue, New York 1, 1960. Price: $10.

This is a very good book. It is probably the most comprehensive book which has yet been written on hurricanes and covers every aspect of the subject (except mathematical theories). It should certainly be read by every forecaster in the area and by anyone contemplating research on the subject. There are eyewitness accounts from the ground and from the air, details of the life-history of hurricanes and a comprehensive summary of techniques for forecasting movement and development though, as the authors agree, there is still much room for research in this field. A chapter, which would be of particular interest to readers living in areas affected by hurricanes, concerns preparations to guard against damage.

The book is well printed, and the tables and diagrams are well placed in relation to the text. Most of the diagrams are clear, though the numerals in those on pages 176 and 177 are too small. A friend of the reviewer, not a professional meteorologist, describes it as "a most readable book" and adds "a word of praise must be given to the very useful Glossary of Meteorological Terms and the Indexes".

S. E. VIRGO

Magyarorszác, Eghajlati Atlasza, Klimaatlas Von Ungarn (Climatological atlas of Hungary). 19 in. × 13 in., pp. 20+78, *illus.*, Akadémiai Kiadó-Budapest, 1960.

The atlas under review contains 130 charts most of which are on a scale of 1:1,250,000 and the rest on 1:2,500,000. The contents and descriptions are in German as well as Hungarian on a loose inset.

The volume opens with four maps of topography, soil types and vegetation. The climatic charts cover hours of sunshine, cloudiness, fog, actual (that is, unreduced) temperature, frost duration, dates of first and last frost, frequencies of "frost", "ice", "extreme heat" etc. days, vapour pressure, relative humidity at 1400, precipitation amounts and frequencies of days of precipitation of over one millimetre etc., evapotranspiration, amount of snowfall, duration of days of snow and snow lying, first and last dates of snow, wind roses and mean isobars, synoptic charts for six characteristic weather situations, temperature extremes shown by mean isotherms of the warmest and coldest winter and summer months, extremes of precipitation in similar form and phenology. Pillar diagrams of mean monthly rainfall at a number of stations are also given. The periods vary but are mostly for 1901 to 1950 and two of the extreme months are taken from before 1910. The charts for the various elements are not all given for the same portions of the year; the portions are changed to suit the natural variations of the elements. No element has twelve-monthly mean charts but means for mid-season months are given for many. The selection has been carefully made to give the best impression of the variations and extremes in minimum space.

The printing is very good. The areas between isopleths are coloured to harmonious schemes which vary with the element. This atlas is an excellent production and the reviewer's only criticism is that he would have liked to have seen German as well as Hungarian titles and legends on the maps themselves.

G. A. BULL

Weather forecasting for aeronautics, by J. J. George. 10¼ in. × 6¾ in., pp. ix+673, *illus.*, Academic Press, New York and London, 1960. Price: £5 7*s*. 6*d*.

The title of this book gives a good idea of its contents except that the words "in the U.S.A." should have been added. The author, assisted by seven other contributors, is a meteorologist with Eastern Air Lines, and the book is almost wholly concerned with weather forecasting in relation to the operation of an airline in the United States of America.

In the first somewhat philosophical chapter the author stresses the economic value of weather forecasts. No forecast is certain; each forecast has a probability of success, and when considering the economic operations of an airline it is the probability of occurrence of a weather phenomenon which must be evaluated. The simple economics equation is that protective measures for an eventuality should be taken if the probability of its occurrence $P > C/L$ where C is the cost of taking preventative measures, and L is the loss which would result if these measures were not taken and the adverse eventuality materialized. Prediction diagrams are extensively used in the forecasting techniques described in the book and from these, in most cases, the probability of the meteorological eventuality can be estimated.

Eight chapters are concerned with the production of forecast charts. The chapter on the prediction of cyclogenesis (45 pages) is very thorough: the author describes methods of determining whether or not cyclogenesis will occur, and if it does whether it will take the form of deepening of the parent cyclone, or formation of a new cyclone, or of a centre jump. He then describes objective methods of determining the location of new cyclogenesis, its timing, the future intensity, the future track and the predicted speed. An even more extensive chapter (94 pages) is concerned with the movement, deepening and filling of cyclones, and objective methods are described for forecasting their development, speed, direction of movement and time of recurving.

These two are the most comprehensive chapters, but very useful and important are the following five chapters dealing with the movement of anticyclones in North America, the movement of cold lows at the 500-millibar level, the displacement of surface cold fronts, warm frontal analysis and movement, and the movement of tropical cyclones. A chapter entitled "the poor-man's numerical weather prediction system" completes the chapters concerned with the production of forecast charts.

The next four chapters are concerned with forecasting weather phenomena. There is a chapter on the prediction of very low ceilings and fogs, followed by one on pre-trough winter precipitation in which the author produces prediction diagrams for forecasting the amounts of precipitation. There then follows a chapter on the prediction of severe weather, thunderstorms, line squalls, turbulence, hail, tornadoes and aircraft icing—the latter is dismissed in a page as a phenomenon which can no longer be regarded as a hazard. Heavy snowstorms are discussed in a short chapter, wind and temperature forecasting at length, and there is a very lucid short chapter on the use of radar. The last hundred pages of the book are concerned with local forecast studies for airfields in the United States.

This is a first-class stimulating book. It is generously illustrated and it is so well written that the formidable task of reading 662 pages becomes at once a pleasure. What is wholly admirable about the book is its straightforwardness: it is what it professes to be, a handbook for forecasters, and while underlying theories are sometimes mentioned the emphasis is in describing forecasting methods. What is impressive is the variety of the forecasting methods; the parameters for the prediction diagrams are derived variously from surface, 850, 700 and 500-millibar charts, sometimes they are isotherm gradients, sometimes wavelengths or amplitudes; clearly the methods result from a great deal of trial and error, based on theory, and the charts and methods described are those which have been found by experience to give the best results.

The main value to the British forecaster of reading the book lies in its stimulus since probably none of the forecasting methods described as suitable for the United States can be used in the United Kingdom without modification. The book shows what can be done if a real effort is made. A great deal of operational research has been carried out in the United States of the kind that is necessary to bridge the gap between the theoretical work of the Rossbys, the Scherhags and the Sutcliffes, and the operational demands of the forecaster on the bench. This excellent book might be regarded as part of the dividends paid by that operational research.

R. A. HAMILTON

OBITUARY

Mr. Edward William Barlow, B.Sc.—It is with deep regret that we record the death of Mr. E. W. Barlow in his 74th year, on 9 January 1961, after a retirement of only two years. A short sketch of his career appeared in the *Meteorological Magazine* of January 1959.

Mr. Barlow's 39 years' service in the Meteorological Office, which he joined as a Senior Professional Assistant after service with the R.N.A.S. and R.A.F. in the First World War, was noteworthy in that he spent no fewer than 32 years in the Marine Division. Here he was primarily concerned with ocean currents and sea-ice, the preparation of the atlases on these subjects, based on observations sent in by British ships, and the corresponding text in the 73 volumes of the *Admiralty Pilots*, all of which he revised once, a number twice and a few three times, as fresh knowledge made a new edition possible.

He was responsible also for the selection of items from the meteorological logbooks of ships of the voluntary observing fleet for publication in our contemporary, *The Marine Observer*, and as an expert on various natural phenomena frequently contributed explanatory notes for them. His particular study was bio-luminescence, and on this subject he continued to advise the Marine Division after his retirement. L.B.P.

HONOUR

The following award was announced in the New Year Honours List, 1961:

C.B.E.

W. A. Grinsted, Director of the West Indies Meteorological Service.

METEOROLOGICAL OFFICE NEWS

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

Mr. C. J. G. Budd, Senior Experimental Officer, who retired on 28 December 1960. He joined the Office in June 1920 as a Technical Assistant at Croydon. In 1925 he was transferred to the Aviation Services Division at Headquarters where he remained for some nine years, except for a short spell at an aviation outstation in 1927. Since 1934 he served continuously at aviation outstations including a tour of duty at Malta. From 1948 until his retirement he served at Uxbridge.

Mr. H. Gingell, Senior Assistant (Scientific), who retired on 17 December 1960. He joined the Office in January 1936 as an Observer, Grade II. The greater part of his service has been spent at aviation outstations including a tour of duty in Iraq. He also served for short spells in the Instruments Division in 1945–6 and the British Climatology Division in 1954. In 1955 he was transferred to the London Forecasting Office where he remained until his retirement.

Staff suggestions scheme

Mr. F. B. Swain, Experimental Officer, was awarded £25 for a suggestion leading to the introduction in the Meteorological Office of simplified topographical maps.